



A literature review and classification of recommender systems research

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ABSTRACT

Recommender systems have become an important research field since the emergence of the first paper on collaborative filtering in the mid-1990s. Although academic research on recommender systems has increased significantly over the past 10 years, there are deficiencies in the comprehensive literature review and classification of that research. For that reason, we reviewed 210 articles on recommender systems from 46 journals published between 2001 and 2010, and then classified those by the year of publication, the journals in which they appeared, their application fields, and their data mining techniques. The 210 articles are categorized into eight application fields (books, documents, images, movie, music, shopping, TV programs, and others) and eight data mining techniques (association rule, clustering, decision tree, k-nearest neighbor, link analysis, neural network, regression, and other heuristic methods). Our research provides information about trends in recommender systems research by examining the publication years of the articles, and provides practitioners and researchers with insight and future direction on recommender systems. We hope that this paper helps anyone who is interested in recommender systems research with insight for future research direction.

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1. Introduction

Recommender systems have become an important research area since the emergence of the first research paper on collaborative filtering in the mid-1990s (Resnick, Iakovou, Sushak, Bergstrom, & Riedl, 1994; Shardanand & Maes, 1995). In general, recommender systems directly help users to find content, products, or services (such as books, digital products, movies, music, TV programs, and web sites) by aggregating and analyzing suggestions from other users, which mean reviews from various authorities, and users (Frias-Martinez, Chen, & Liu, 2009; Frias-Martinez, Magoulas, Chen, & Macredie, 2006; Kim, Ji, Ha, & Jo, 2010). These systems use analytic technology to compute the probability that a user will purchase one of the products at each place, so that users will receive recommendations for the right products to purchase.

Recommender systems are generally classified into collaborative filtering (CF) and content-based filtering (CB). In general, CF uses an information filtering technique based on the user's previous evaluation of items or history of previous purchases. However, this technique has been known to reveal two major issues: sparsity problem and the scalability problem (Claypool et al., 1999; Sarwar, Karypis, Konstan, & Riedl, 2000a, 2000b). In contrast, CB analyzes a set of documents rated by an individual user and uses the contents of the documents, as well as the provided ratings, to infer a user profile

that can be used to recommend additional items of interest (Basu, Hirsh, & Cohen, 1998). However, the syntactic nature of CB, which detects similarities between items that share the same attribute or characteristic, causes overspecialized recommendations that only include items very similar to those of which the user is already aware (Lopez-Nores, Garca-Duque, Frenandez-Vilas, & Bermejo-Munoz, 2008).

Over the last decade, most of researchers have studied new approaches of recommender systems in order to solve these problems of CF and CB, and to implement them into real world situations. Specifically, applying data mining techniques to recommender systems has been effective in providing personalized information to the user by analyzing his or her preferences.

However, more research is needed to be applicable in real world situations because research fields on recommender systems are still broader and less mature than in other research areas. Therefore, the existing articles on recommender systems must be reviewed with an eye toward the next generation of recommender systems, which will improve recommendation methods to offer more useful and appropriate information to users.

In this research, we reviewed and classified articles on recommender systems that were published in academic journals between 2001 and 2010, in order to gain insight on recommender systems. This research is organized as follows:

- (1) The research methodology used in this study is reported.
- (2) Criteria for classification of research papers on recommender systems are presented.

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- (3) Research papers on recommender systems are analyzed and the results of their classifications are presented.
- (4) Conclusions are presented, and the limitations and implications of this study are discussed.

We hope that this research will accentuate the importance of recommender systems and provide researchers and practitioners with insight on recommender systems research.

2. Research methodology

The purpose of this study is to understand the trend of recommender systems research by examining the published articles, and to afford practitioners and academics with insight and future direction on recommender systems.

Hence, we will verify the distribution of research papers on recommender systems by their year of publication, and classify the research papers by the data mining techniques used for recommendation and by the application fields used. However, considering the nature of research on recommender systems, it would be difficult to confine each paper to a specific discipline. Additional proof of this difficulty can be seen from the fact that research papers on recommender systems are scattered across diverse journals such as marketing, information technology, information science, computer science, and management. As a result, it is necessary to compile the increasing number of research papers on recommender systems systematically. The following electronic journal databases were searched to provide a comprehensive bibliography of research papers on recommender systems:

- ABI/INFORM Database;
- ACM Portal;
- EBSCO Academic Search Premier;
- EBSCO Business Source Premier;
- IEEE/IEE Library;
- Science Direct.

The search process of research papers on recommender systems was performed on the top 125 MIS journals. The search was performed based on five descriptors: "Recommender system", "Recommendation system", "Personalization system", "Collaborative filtering", and "Contents filtering". Two authors reviewed the full text of each research paper, and papers that were not truly related to recommender systems were deleted if the two authors agreed to do so. If the authors' opinions were different, another author reviewed the paper and decided whether to delete it or not. The following research papers, set forth in the description below, were excluded because they were unfit for our research:

- Conference papers, master's and doctoral dissertations, textbooks, unpublished working papers, non-English papers, and news articles were eliminated. Unlike these publications, papers published by academic journals are thought to be reliable and worthy of comment, because they are published after peer review.
- Because research on recommender systems is relatively current, we have only searched research articles published between 2001 and the end of 2010. This 10-year period is considered to be representative of recommender systems research.
- Only research papers that described how recommender systems can be applied were chosen.

We selected 210 research papers on recommender systems from 46 journals. Each research papers was prudently reviewed and classified into one of the eight categories in the application fields

and data mining techniques. Although the investigation was not exhaustive, it provides as a comprehensive basis for understanding recommender system research.

3. Classification method

Our classification framework consists of recommendation fields and data mining techniques. In this research, we classify the research papers that were reviewed into eight categories of application fields and eight categories of data mining techniques. The overall graphical classification framework for recommender systems research papers is presented in Fig. 1.

3.1. Classification framework for application fields

Many recommender systems have been used to provide users with information to help them decide which products to purchase (Schafer, Joseph, & Riedl, 2001). However, it is not easy to find papers that classify research papers systematically, even though recommender systems have been applied to diverse business areas. Accordingly, it is meaningful to investigate application fields. Our research adopts the basic classification scheme of Schafer et al., 2001, who have classified recommendation applications by real world, such as books, movies, music, shopping and others. We classify research papers by application fields such as books, documents, images, movies, music, shopping, TV programs and others. Through in-depth reviews of research papers, classifying shopping fields involves online, offline, and mobile shopping product, classifying document fields involves papers, blogs and web pages. Also, other fields involve a minority of recommendation fields such as hotel, travel, and food.

3.2. Classification framework for data mining techniques

In general, data mining techniques are defined as extracting or mining knowledge from data. These techniques are used for the exploration and analysis of large quantities of data in order to discover meaningful patterns and rules (Berry & Linoff, 2004). They can be used to lead decision making and to predict the effect of decisions. Significantly, many researchers have used data mining techniques to improve the performance of recommender systems. Consequently, it is meaningful to classify the research papers according to data mining techniques. We widely classified data mining techniques into the following eight categories: association rule, clustering, decision tree, k-nearest neighbor, link analysis, neural network, regression, and other heuristic methods.

- (1) **Association rule:** Association rule mining refers to the discovery of all association rules that are above user-specified minimum support and minimum confidence levels. Given a set of transactions in which each transaction contains a set of items, an association rule applies the form $X \Rightarrow Y$, where X and Y are two sets of items (Cho, Kim, & Kim, 2002).
- (2) **Clustering:** The clustering method identifies a finite set of categories or clusters to describe data. Among the clustering methods, the most popular are K-means and self-organizing map (SOM). K-means takes the input parameter, K, and partitions a set of n objects into K clusters (Berry & Linoff, 2004). SOM is a method for an unsupervised learning, based on an artificial neurons clustering technique (Lihua, Lu, Jing, & Zongyong, 2005).
- (3) **Decision tree:** Most popular classification methods are decision tree induction. Decision tree induction techniques build decision trees to label or categorize cases into a set of known

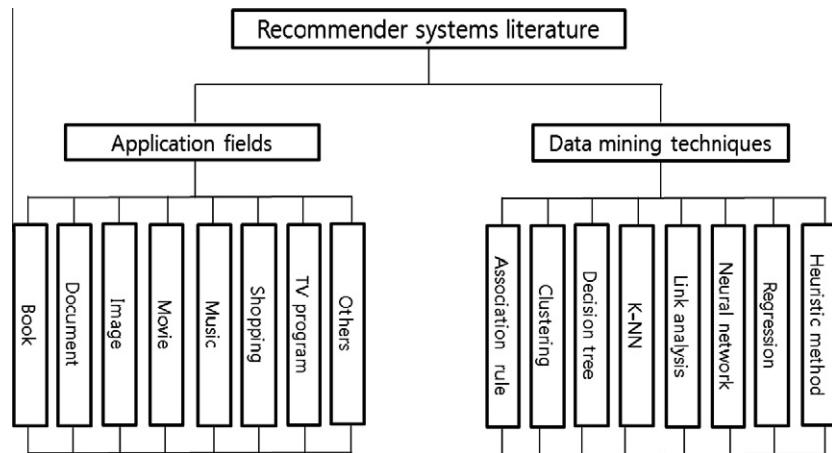


Fig. 1. Classification framework.

classes. The top node in a tree is called as a root node. A decision tree is a tree in which each internal (non-leaf) node represents a test on an attribute, each branch represents an outcome of the test, and each terminal (leaf) node represents a class prediction (Kim, Cho, Kim, Kim, & Suh, 2002).

- (4) *k-Nearest neighbor*: The k-NN (*k*-nearest neighbor) model, a typical traditional CF-based recommender system, makes recommendations according to the following three phases. (1) Recommender systems construct a user profile using the user's preference ratings, which are obtained either directly from explicit ratings of items or indirectly from purchase or usage information. (2) Recommender systems apply statistical or machine learning techniques to discover *k* users, known as neighbors or recommenders, who in the past have shown similar behaviors. A neighborhood is formed based on the degree of similarity between a mark user and other users. (3) Once a neighborhood is formed for a target user, recommender systems make a top-*n* item set that the target user is most likely to purchase by analyzing the items in which neighbors have exhibited interest (Kim, Kim, & Ryu, 2009).
- (5) *Neural network*: A neural network is a parallel distributed information processing system that is able to learn and self-organize. This system consists of a large number of uncomplicated processing entities which are interconnected to form a network that conducts complex computational tasks (Ibnkahla, 2000). A neural network builds a class of very pliable model that can be used for a diversity of different applications, such as prediction, non-linear regression, or classification (Anders & Korn, 1999).
- (6) *Link analysis*: Link analysis discovers relations between domains in large databases. One type of link analysis, social network analysis is a sociological approach for analyzing patterns relationships and interactions between social actors in order to find a fundamental social structure. Also, link analysis has presented great potential in improving the accuracy of web searches. Link analysis consists of PageRank and HITS algorithms. Most link analysis algorithms handle a web page as a single node in the web graph (Cai, He, Wen, & Ma, 2004).
- (7) *Regression*: Regression analysis is a powerful process for analyzing associative relationships between dependent variables and one or more independent variables. It has been used for curve fitting, prediction, and testing systematic hypotheses about relationships between variables (Malhotra, 2007).

(8) *Other heuristic methods*: Heuristic methods have been developed by adding new method to existing methods. Heuristic methods include mixture models and the, ontology method.

3.3. Classification process

Each of the selected research papers was reviewed and classified according to the proposed classification framework by two of the four authors of this paper (first team). The other two authors (second team) made a final verification of the classification results. The classification process is composed of the following four steps:

- (1) Electronic database search.
- (2) Initial classification by one of the two researchers in the first team.
- (3) Independent verification of classification results by the other researcher in the first team.
- (4) Final verification of classification results discussed by the second team.

The selected criteria and evaluation framework is represented in Fig. 2. The research papers were analyzed by year of publication, by journals in which the research papers were published, and by application fields and data mining techniques.

4. Classification of research papers

We selected a total of 210 research papers from 46 journals and classified them according to the classification framework. The results of our analysis will supply guidelines for future research on recommender systems. The details are described below.

4.1. Distribution by year of publication

The distribution of research papers by year of publication between 2001 and 2010 is shown in Fig. 3. It is apparent that publications related to recommender systems steadily increased between 2000 and 2004, and rapidly increased between 2007 and 2010. The decrease of research papers between 2005 and 2006 is thought to be because recommender systems research apparently extended a new application field between 2005 and 2006. Whereas a majority of recommender systems research between 2005 and 2006 were limited to movie and shopping fields,

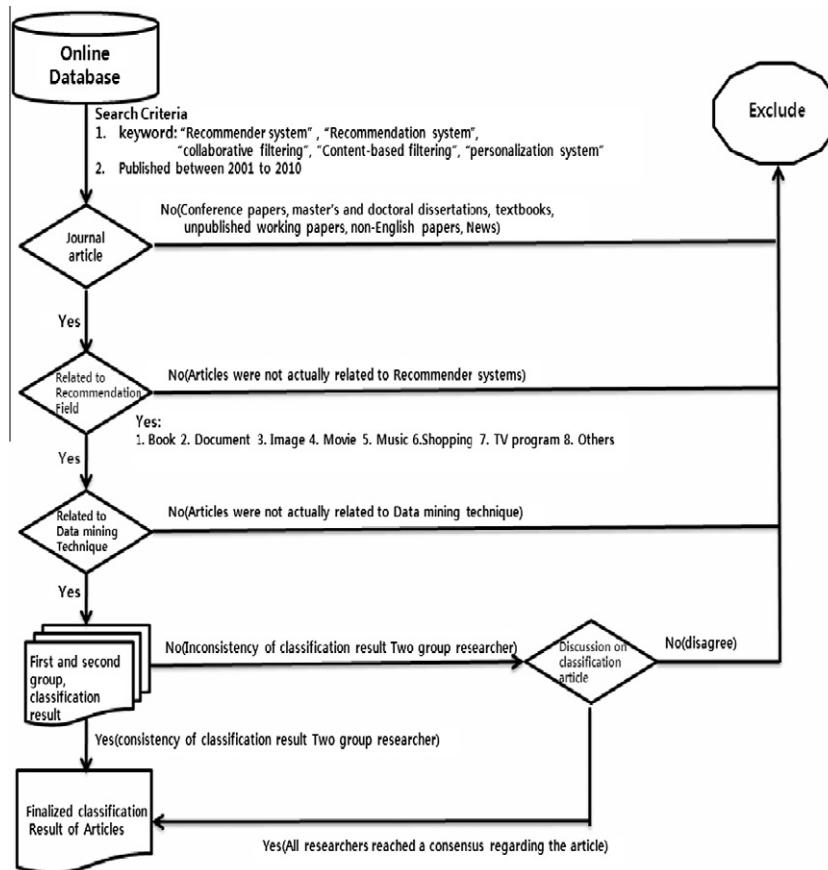


Fig. 2. Selection criteria and evaluation framework.

this research began to extend to other fields such as books, documents, music and other fields in 2007.

4.2. Distribution by journal

Research papers are selected from a total of 46 different journals. Distribution of research papers by journal is presented in Table 1. Expert Systems with Applications published more than 33% (70 out of 210 research papers, or 33.33%) of the total number of research papers. IEEE Intelligent System (21 out of 210 research papers, or 10.00%), along with, Decision Support Systems and ACM Transactions on Information Systems (12 out of 210 research papers, or 5.71%), published the second and third largest percentage of recommender systems-related research papers among the journals. The most research papers were published in Expert Systems with Applications, because this journal focuses on knowledge of the application of expert and intelligent system by industry, governments and universities worldwide (Ngai, Xiu, & Chau, 2009).

4.3. Distribution by application fields and data mining techniques

Distribution of research papers by application fields is represented in Fig. 4. The majority of the research papers were related to movie (53 out of 210 research papers, or 25.2%) and shopping (42 out of 210 research papers, or 20.0%). Because recommender systems in movie and shopping fields have a larger number of practical applications than other fields, it is inferred that although many research papers were published, few of them were related to image fields (7 out of 210 research papers, or 3.3%), and music, and TV program fields (9 out of 210 research papers, or 4.2% respectively). In particular, because the data of MovieLens (www.movielens.org/)

are freely accessed, many recommendation methodologies have been proposed and evaluated with MovieLens data, which explains why there is more the recommender systems researches in movie fields than in other fields.

Distribution of research papers by application fields and journal is represented in Table 2. Among the application fields and journals, Expert Systems with Applications included most of the application fields. However, research papers about recommending music and TV programs were usually published in more specific journals. Because music and TV program related papers are usually published at the specific journals.

Distribution of research papers by data mining techniques is shown in Fig. 5, and distribution of the 210 research papers classified by the suggested classification framework is shown in Table 3. Among data mining techniques, the heuristic and k-NN (k-nearest

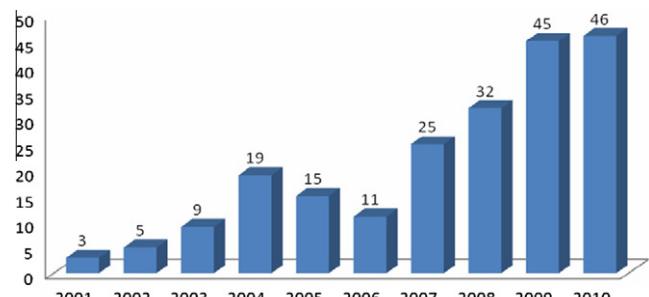
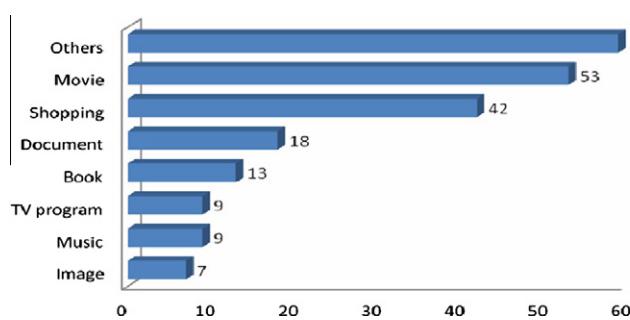


Fig. 3. Distribution of research papers by year of publication.

Table 1

Distribution of research papers by journal in which the research papers were published.

Journal title	Amount	Percentage (%)
Expert Systems with Applications	70	33.33
IEEE Intelligent Systems	21	10.00
ACM Transactions on Information Systems	12	5.71
Decision Support Systems	12	5.71
Knowledge-Based Systems	11	5.24
IEEE Internet Computing	9	4.29
IEEE Transactions on Consumer Electronics	9	4.29
International Journal of Electronic Commerce	7	3.33
Electronic Commerce Research & Applications	6	2.86
IEEE Transactions on Knowledge and Data Engineering	6	2.86
IEEE Transactions on Audio, Speech, and Language Processing	3	1.43
International Journal of Human Computer Studies	3	1.43
Journal of Systems & Software	3	1.43
Behavior & Information Technology	2	0.95
Computers in Human Behavior	2	0.95
Information Processing & Management	2	0.95
IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans	2	0.95
Management Science	2	0.95
ACM Transactions on Computer-Human Interaction	1	0.48
ACM Transactions on Knowledge Discovery from Data	1	0.48
AI Magazine	1	0.48
Communications of the ACM	1	0.48
Computer	1	0.48
Computer Supported Cooperative Work	1	0.48
Computers & Operations Research	1	0.48
Electron Markets	1	0.48
IEEE Circuits and Systems for Video Technology	1	0.48
IEEE Pervasive Computing	1	0.48
IEEE Security & Privacy	1	0.48
IEEE Software	1	0.48
IEEE Spectrum	1	0.48
IEEE Transactions on Fuzzy Systems	1	0.48
IEEE Transactions on Information Forensics and Security	1	0.48
IEEE Transactions on Multimedia	1	0.48
IEEE Transactions on Pattern Analysis and Machine Intelligence	1	0.48
IEEE Transactions on Services Computing	1	0.48
IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews	1	0.48
Information & Management	1	0.48
Information Systems	1	0.48
International Journal of Information Management	1	0.48
International Journal of Technology Management	1	0.48
IT Professional	1	0.48
Journal of Computer Information Systems	1	0.48
Journal of Software Maintenance	1	0.48
Journal of Management Information Systems	1	0.48
Journal of Information Science	1	0.48
Total	210	100.00

**Fig. 4.** Distribution of research papers by application fields.

neighbor) models have been used the most often in application fields. Because, the heuristic model is not one method but instead involves adding on new methods to existing diverse methods, it is used to expand advanced research. Also, the CF system is one of the most successful methodologies in recommender systems, and k-NN is a popular type of CF, so k-NN has been applied in most of the application fields.

4.4. Distribution of research papers by publication years and application fields

Distribution of research papers by publication years and application fields is shown in Fig. 6, which shows decreases in most of the application fields during 2006. Until 2006, most recommender systems research was focused on movies and shopping fields. However, the focus of recommender systems research has extended not only to movie and shopping fields, but also to books, documents, music, and other fields beginning in 2007.

4.5. Distribution of research papers by publication years and data mining techniques

Distribution of research papers by publication years and data mining techniques is shown in Fig. 7. Among the data mining techniques, most of the techniques are decreased in 2006, except that the heuristic method increased steadily and reached a peak in 2010. Because the heuristic method is not only one method, but rather involves diverse methods that are not included in other server data mining techniques, its usage has increased annually.

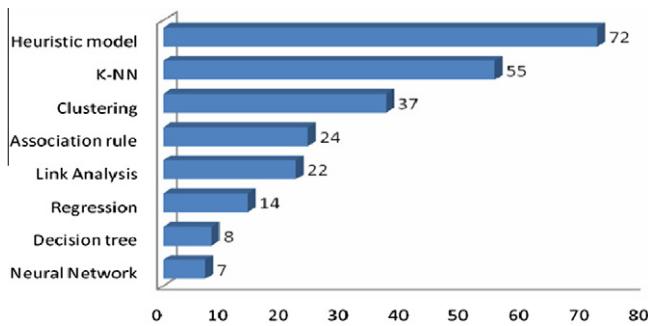
Table 2

Distribution of research papers by recommendation field and journals.

Field	Journal	Amount
Book	ACM Transactions on Information Systems	2
	Decision Support Systems	2
	Electronic Commerce Research & Applications	2
	IEEE Internet Computing	2
	Computers in Human Behavior	1
	Expert Systems with Applications	1
	International Journal of Information Management	1
	Knowledge-Based Systems	1
	Management Science	1
		13
Document	Expert Systems with Applications	5
	IEEE Intelligent Systems	3
	ACM Transactions on Information Systems	2
	Decision Support Systems	2
	IEEE Internet Computing	1
	IEEE Transactions on Information Forensics and Security	1
	Journal of Computer Information Systems	1
	Journal of Systems & Software	1
	Knowledge-Based Systems	1
	International Journal of Human Computer Studies	1
Image		18
	Expert Systems with Applications	4
	Journal of Information Science	1
	IEEE Intelligent Systems	1
Movie	IEEE Transactions on Multimedia,	1
	Expert Systems with Applications	21
	ACM Transactions on Information Systems	6
	Knowledge-Based Systems	5
	International Journal of Electronic Commerce	4
	IEEE Intelligent Systems	3
	Electronic Commerce Research & Applications	2
	IEEE Internet Computing	2
	IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans	2
	ACM Transactions on Knowledge Discovery from Data	1
Music	Behavior & Information Technology	1
	Communications of the ACM	1
	Computer	1
	Decision Support Systems	1
	IEEE Circuits and Systems for Video Technology	1
	IEEE Transactions on Knowledge and Data Engineering	1
	Information Processing & Management	1
		53
		9
Others	IEEE Transactions on Audio, Speech, and Language Processing	3
	Expert Systems with Applications	2
	ACM Transactions on Information Systems	1
	IEEE Intelligent Systems	1
	IEEE Transactions on Consumer Electronics	1
	Information Processing & Management	1
		22
	Expert Systems with Applications	8
	IEEE Intelligent Systems	5
	IEEE Transactions on Knowledge and Data Engineering	4
	Decision Support Systems	3
	IEEE Internet Computing	3
	IEEE Transactions on Consumer Electronics	2
	International Journal of Electronic Commerce	1
	Computer Supported Cooperative Work	1
	Electron Markets	1
Shopping	IEEE Pervasive Computing	1
	IEEE Security & Privacy	1
	IEEE Software	1
	IEEE Spectrum	1
	IEEE Transactions on Fuzzy Systems	1
	IEEE Transactions on Pattern Analysis and Machine Intelligence	1
	IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews	1
	IT Professional	1
	Knowledge-Based Systems	1
	Management Science	1
		59
Shopping	Expert Systems with Applications	14
	IEEE Intelligent Systems	5

Table 2 (continued)

Field	Journal	Amount
	Decision Support Systems	3
	Electronic Commerce Research & Applications	2
	International Journal of Human Computer Studies	2
	Knowledge-Based Systems	2
	ACM Transaction on Computer-Human Interaction	1
	ACM Transactions on Information Systems	1
	AI Magazine	1
	Behavior & Information Technology	1
	Computers & Operations Research	1
	IEEE Transactions on Consumer Electronics	1
	IEEE Transactions on Services Computing	1
	Information & Management	1
	Information Systems	1
	International Journal of Electronic Commerce	1
	International Journal of Technology Management	1
	Journal of Software Maintenance	1
	Journal of Systems & Software	1
	Journal of Management Information Systems	1
		42
TV program	IEEE Transactions on Consumer Electronics	4
	Computers in Human Behavior	1
	Expert Systems with Applications	1
	IEEE Internet Computing	1
	Journal of Systems & Software	1
	Knowledge-Based Systems	1
		9
Total		210

**Fig. 5.** Distribution of research papers by data mining techniques.

Based on their previous rates of change, more heuristic methods are expected to be used significantly in the future.

5. Conclusion, research implication and future work

Recommender systems have attracted the attention of academics and practitioners. In this research, we have identified 210 research papers on recommender systems, which were published between 2001 and 2010, to understand the trend of recommender systems-related research and to provide practitioners and researchers with insight and future direction on recommender systems. The results represented in this paper have several significant implications:

- Based on previous publication rates, interest in recommender systems related research will grow significantly in the future.
- Fifty-three research papers were related to movie recommendations, whereas image recommendations were identified in only seven research papers. Image field, and Music, and TV program recommendations were identified in nine research papers respectively. Therefore, more research is required to for image,

music and TV program recommendations. This result was due to the easy use of the MovieLens data set. Therefore, it looks to be necessary to prepare data sets in other fields.

- Among the 210 research papers, 55 research papers used k-NN and 72 research papers have used heuristic models in the recommender system domain. k-NN creates applied user profile using the user's preference ratings obtained either directly from the user's explicit ratings of items or indirectly from the user's purchase or usage information. Therefore, it is not surprising that the k-NN method has been used in an extensive range of recommender systems domains. Also, because the heuristic model is not a single method, but one that consist of existing diverse methods, its use will be increased.
- Research papers using clustering and association rule techniques rank behind k-NN. From this, we know that both clustering and association rule techniques have been widely used in real business application than other techniques.
- Recently, social network analysis has been used in various applications. However studies on recommender systems using social network analysis are still deficient. Henceforth, we expect that new recommendation approaches using social network analysis will be developed. Therefore, developing the recommendation system research using social network analysis will be an interesting area further research.
- The number of heuristic methods is increasing every year. This result has been caused by the many researchers developing new methodologies and mixed technique model.
- Our research is significant because the majority of recommender systems research has been published in 125 MIS journals, such as ACM, IEEE publications. However, recommender systems research has shifted from the MIS field to various business fields, so we expect to see more recommender systems research published in management and business journals.

Our classification model will provide the practitioner and academic with guideline for future research on recommender systems. However our research has the following limitations: First,

Table 3

Distribution of research papers by application fields and journals.

Recommendation field	Data mining techniques	Reference
Book	Heuristic model	Riedl (2001)
	Clustering	Linden, Smith, and York (2003)
	k-NN	McSherry (2004)
	Link analysis	Huang, Chen, and Zeng (2004)
	Link analysis	Huang, Zeng, and Chen (2007a, 2007b)
	Link analysis	Ziegler and Golbec (2007)
	Regression	Hernández del Olmo and Gaudiosio (2008)
	Clustering	Rosaci, Sarné, and Garruzzo (2009)
	k-NN, heuristic model	Kim, Kim, Oh, and Ryu (2010)
	Association rule, k-NN	Kim et al. (2010)
	Heuristic model, link analysis	Hwang, Wei, and Liao (2010)
	Heuristic model	Crespo et al. (2010)
Document	k-NN, neural network, regression	Lee, Hui, and Fong (2002)
	Association rule, clustering	Wang and Shao (2004)
	Heuristic model	Middleton, Shadbolt, and De Roure (2004)
	Clustering, neural network	Lihua et al. (2005)
	Heuristic model	Melamed, Shapira, and Elovici (2007)
	Link analysis	Liang, Yang, Chen, and Ku (2008)
	Heuristic model	Weng and Chang (2008)
	Clustering	Wei, Yang, and Hsiao (2008)
	k-NN, regression	Tang and McCalla (2009)
	Clustering	Lai and Liu (2009)
	Association rule, clustering, Link analysis	Göksedef and Gündüz-Öğüdücü (2010)
	Heuristic model	Champin, Briggs, Coyle and Smyth (2010)
	Heuristic model	Moens, De Beer, Boij, and Gomez (2010)
Image	Clustering, heuristic model	Jalali, Mustapha, Sulaiman, and Mamat (2010)
	Link analysis	Dell'Amico and Capra (2010)
	Heuristic model	Kwon (2003)
	Heuristic model	Kim, Lee, Cho, and Kim (2004)
	Heuristic model	Boutemedjet and Ziou (2008)
	k-NN	Lee, Park, and Park (2008)
Movie	k-NN	Kim, Kim, and Cho (2008)
	k-NN	Lee, Park, and Park (2009)
	Heuristic model, k-NN	Nan Zheng, Li, Liao, and Zhang (2010)
	k-NN	Naren, Benjamin, Batul, Ananth, and George (2001)
	Association rule	Herlocker and Konstan (2001)
	Association rule, decision tree, k-NN	Cheung, Kwok, Law, and Tsui (2003)
	Clustering, k-NN	Roh, Oh, and Han (2003)
	Clustering	Cheung, Tsui, and Liu (2004)
	k-NN	Han, Xie, Yang, and Shen (2004)
	Clustering, k-NN	Weng and Liu (2004)
	k-NN	Zeng, Xing, Zhou, and Zheng (2004)
	k-NN	Herlocker, Konstan, Terveen, and Riedl (2004)
	Link analysis	Miller, Konstan, and Riedl (2004)
	Clustering, k-NN	Min and Han (2005)
	k-NN	Li, Lu, and Xuefeng (2005)
	Clustering	Kim and Yum (2005)
	Regression	Lee, Jun, Lee, and Kim (2005)
	Heuristic model	Adomavicius, Sankaranarayanan, Sen, and Tuzhilin (2005)
	Heuristic model	Salter and Antonopoulos (2006)
	Association rule, k-NN	Du Boucher-Ryan and Bridge (2006)
	Heuristic model	Prangl, Szkaliczki, and Hellwagner (2007)
	k-NN	Hurley, O'Mahony and Silvestre (2007)
	Heuristic model	Im and Hars (2007)
	Clustering, k-NN	Symeonidis, Nanopoulos, and Manolopoulos (2008)
	k-NN	Symeonidis, Nanopoulos, Papadopoulos, and Manolopoulos (2008)
	k-NN	Chen, Cheng, and Chuang (2008)
	Association rule	Leung, Chan, and Chung (2008)
	Heuristic model	Russell and Yoon (2008)
	k-NN	Lee and Olafsson (2009)
	k-NN	Jeong, Lee, and Cho (2009a)
	k-NN	Jeong, Lee, and Cho (2009b)
	Clustering, k-NN	Merve and Arslan (2009)
	k-NN	Koren, Bell, and Volinsky (2009)
	k-NN	Chen, Wang, and Zhang (2009)
	Clustering	Kwon, Cho, and Park (2009)
	Heuristic model	Cho, Kwon, and Park (2009)
	Heuristic model	Yang and Li (2009)
	k-NN	Bobadilla, Serradilla, and Hernando (2009)
	Heuristic model	Julià, Sappa, Lumbreras, Serrat, and López (2009)
	Heuristic model	Koren (2010a)
	Heuristic model	Winoto and Tang (2010)
	Heuristic model	Ahn, Kang, and Lee (2010)

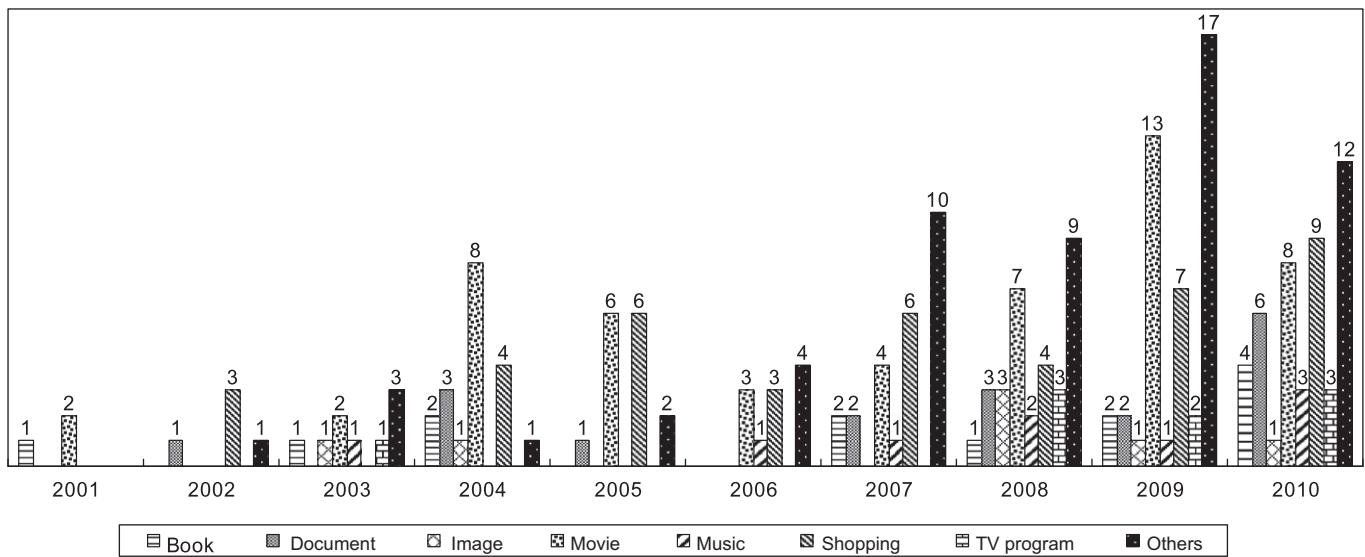
Table 3 (continued)

Recommendation field	Data mining techniques	Reference
Music	Heuristic model, link analysis, regression	Hwang (2010)
	k-NN	Bobadilla, Serradilla, and Bernal (2010)
	Regression	Ozok, Fan, and Norcio (2010)
	Heuristic model, k-NN	Koren (2010b)
	k-NN	Ganesan, Garcia-Molina, and Widom (2003)
	Clustering, regression	Zhu, Shi, Kim, and Eom (2006)
	Clustering	Li, Myaeng, and Kim (2007)
	Association rule, k-NN	Yoshii, Goto, Komatani, Ogata, and Okuno (2008)
	Link analysis	Shao, Ogihara, Wang, and Li (2009)
	Clustering, heuristic model	Su, Yeh, Yu, and Tseng (2010)
Others	Heuristic model	Nanopoulos, Rafailidis, Symeonidis, and Manolopoulos (2010)
	Clustering, neural network	Liu, Hsieh, and Tsai (2010)
	Heuristic model	Taab, Werther, Ricci, Zipf, and Gretzel (2002)
	Neural network	Yuan and Tsao (2003)
	Clustering	Chau, Zeng, Chen, Huang, and Hendriawan (2003)
	Heuristic model	Yang, Knoblock, and Wu (2004)
	Heuristic model	Adomavicius and Tuzhilin (2005)
	Heuristic model	Wei, Moreau, and Jennings (2005a)
	Clustering	Ha (2006)
	Heuristic model	McGinty and Smyth (2006)
	Heuristic model	Park, Kang, and Kim (2006)
	Regression	Gretzel and Fesenmaier (2006)
	Heuristic model	Alexander, Gerhard, and Lars (2007)
	Link analysis	Reichling, Veith, and Wulf (2007)
	Association rule	Adda, Valtchev, Missaoui, and Djeraba (2007)
	Clustering, neural network	Martín-Guerrero, Lisboa, Soria-Olivas, Palomares, and Balaguer (2007)
	k-NN, regression	Lee, Ahn, and Han (2007)
	Clustering	Lee and Park (2007)
	Heuristic model	Adomavicius and Kwon (2007)
Shopping	Heuristic model	Ricci and Nguyen (2007)
	Link analysis	Zeng, Wang, Zheng, Yuan, and Chen (2008)
	Heuristic model	Lin (2008)
	Heuristic model	Liang (2008)
	Heuristic model	Hernández del Olmo and Gaudioso (2008)
	Link analysis	Malinowski, Weitzel, and Keim (2008)
	Clustering	Linden (2008)
	Regression	Moon and Russell (2008)
	Association rule, k-NN	Hsu (2008)
	Link analysis	Wang and Chiu (2008)
	Decision tree , k-NN	Hernández del Olmo, Gaudioso, and Martin (2009)
	Heuristic model	Hsu (2009)
	Heuristic model	Schiaffino and Amandi (2009)
	Heuristic model	Porcel, López-Herrera, and Herrera-Viedma (2009a)
	Heuristic model	Zhen, Huang, and Jiang (2009a)
	Decision tree	Wang, Chiang, Hsu, Lin, and Lin (2009)
	Association rule	Yang and Wang (2009)
	Heuristic model	Porcel, Moreno, and Herrera-Viedma (2009b)
	Link analysis	Arazy, Kumar, and Shapira (2009)
	Heuristic model	Zhen, Huang, and Jiang (2009b)
	Heuristic model	Kim, Jeong, and Baik (2009)
	Heuristic model, neural network	Han and Chen (2009)
	Heuristic model	Lesk (2009)
	Association rule, Clustering, regression	Kwon and Kim (2009)
	Association rule, k-NN	Schiaffino and Amandi (2009)
	Link analysis	Li and Kao (2009)
	Link analysis	Kuo, Chen, and Liang (2009)
	Heuristic model	Symeonidis, Nanopoulos, and Manolopoulos (2010)
	Heuristic model	Pillonetto, Dinuzzo, and De Nicolo (2010)
	Heuristic model	Zhen, Huang, and Jiang (2010)
	Heuristic model	Jalali et al. (2010)
	Heuristic model	Porcel and Herrera-Viedma (2010)
	Heuristic model	Zhan et al. (2010)
	Heuristic model, k-NN	Munoz-Orgaño, Ramírez-González, Muñoz-Merino, and Kloos (2010)
	Heuristic model, k-NN	Blanco-Fernandez, Lopez-Nores, Pazos-Arias, Gil-Solla, and Ramos-Cabrera (2010)
	Heuristic model	Yager, Reformat, and Gumrah (2010)
	Heuristic model	Bergamaschi, Guerra, and Leiba (2010)
	Heuristic model	Backhaus et al. (2010)
	Link analysis, regression	Kato, Kashima, Sugiyama, and Asai (2010)
	Association rule, decision tree	Kim et al. (2002)
	Association rule, decision tree	Cho, Kim & Kim (2002)
	Association rule, clustering	Ha (2002)
	k-NN	Vezina and Militaru (2004)
	Regression	Ant Ozok, Quyin, and Norcio (2004)
	Association rule, k-NN	Wang, Chuang, Hsu, and Keh (2004)

(continued on next page)

Table 3 (continued)

Recommendation field	Data mining techniques	Reference
	k-NN	Cho and Kim (2004)
	Association rule, k-NN	Liu and Shih (2005a)
	Association rule, k-NN	Liu and Shih (2005b)
	Association rule, clustering	Cho, Cho & Kim (2005)
	k-NN, regression	Kim, Yum, Song, and Kim (2005)
	Decision tree	Yu, Ou, Zhang, and Zhang (2005)
	Heuristic model	Wei, Moreau, and Jennings (2005b)
	Clustering	Choi, Kang, and Jeon (2006)
	Heuristic model	Garfinkel, Gopal, Tripathi, and Yin (2006)
	k-NN	Zanker, Jannach, Gordea, and Jessenitschnig (2007)
	Association rule	Zhang and Jiao (2007)
	Association rule	Pu and Chen (2007)
	Clustering, link analysis	Wang, Dai, and Yuan (2008b)
	Clustering	Kim and Ahn (2008)
	Association rule, k-NN	Wang and Wu (2009)
	k-NN	Albadvi and Shahbazi (2009)
	Heuristic model	Pu and Chen (2009)
	k-NN	Kim et al. (2009)
	Association rule, k-NN	Robillard and Dagenais (2009)
	Heuristic model	Moosavi, Nematabakhsh, and Farsani (2009)
	Heuristic model	Martin-Vicente, Gil-Solla, Ramos-Cabrera, Blanco-Fernandez, and Lopez-Nores (2010)
	Heuristic model	Ochi, Rao, Takayama and Nass (2010)
	Heuristic model	Funk, Rozinat, Karapanos, Alves de Medeiros, and Koca (2010)
	Link analysis	Yuan, Guan, Lee, Lee, and Hur (2010)
	Heuristic model	Taha and Elmasri (2010)
	Heuristic model, k-NN	Wang and Wu (2010)
	Heuristic model	Pathak, Garfinkel, Gopal, Venkatesan, and Yin (2010)
	Association rule, heuristic model	Chen and Pu (2010)
TV program	Decision tree	Lee and Yang (2003)
	Heuristic model, link analysis	Blanco-Fernandez, Pazos-arias, Gil-Solla, Ramos-Cabrera, and Lopez-Nores (2008)
	Heuristic model, k-NN	Martinez et al. (2010)
	Heuristic model, k-NN	Martin-Vicente et al. (2010)
	Clustering, heuristic model	Cantador and Castells (2010)

**Fig. 6.** Distribution of research papers by publication year and application fields.

due to the limitations of time and manpower, we only surveyed research papers published between 2001 and 2010, and our searches were based on the top 125 MIS. Therefore, if the research had been extended to cover other journals such as those focused on computer science and, marketing, the results might have been different. Second, our findings are based on articles that were selected solely from academic journals. If articles from conferences had been included, the results would have been more diverse.

Third, our study was conducted based on a search of the following keywords: “Recommender system”, “Recommendation system”, “Personalization system”, “Collaborative filtering”, and “Contents filtering”. Besides these five keywords, we did not search additional keywords, such as “Hybrid Filtering”. Research papers that referred to recommender systems, but did not include any of the five key-words, could not be extracted. We think that recommender systems research also has been published in other lan-

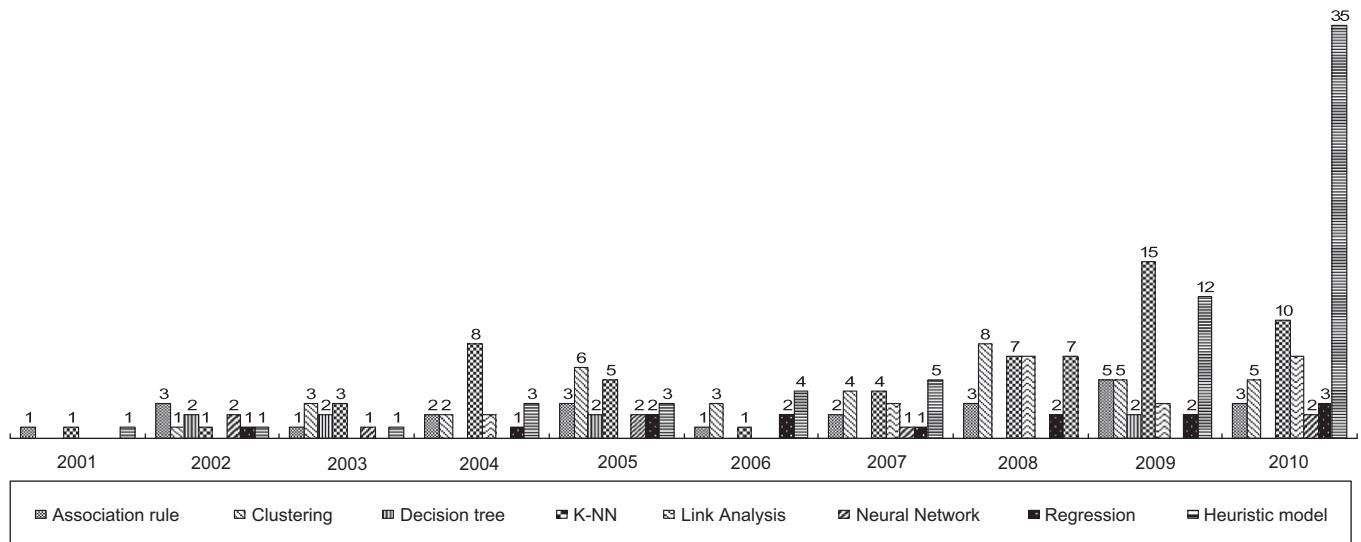


Fig. 7. Distribution of research papers by publication year and data mining technique.

guages. Finally, we classified data mining techniques, but not data mining model.

Accordingly, we will continue to classify articles on an ongoing basis. Moreover, it is also necessary to include conference papers and non-English papers in order to extend our classification model.

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RESEARCH ARTICLE

A systematic literature review of Linked Data-based recommender systems

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SUMMARY

Recommender systems (RS) are software tools that use analytic technologies to suggest different items of interest to an end user. Linked Data is a set of best practices for publishing and connecting structured data on the Web. This paper presents a systematic literature review to summarize the state of the art in RS that use structured data published as Linked Data for providing recommendations of items from diverse domains. It considers the most relevant research problems addressed and classifies RS according to how Linked Data have been used to provide recommendations. Furthermore, it analyzes contributions, limitations, application domains, evaluation techniques, and directions proposed for future research. We found that there are still many open challenges with regard to RS based on Linked Data in order to be efficient for real applications. The main ones are personalization of recommendations, use of more datasets considering the heterogeneity introduced, creation of new hybrid RS for adding information, definition of more advanced similarity measures that take into account the large amount of data in Linked Data datasets, and implementation of testbeds to study evaluation techniques and to assess the accuracy scalability and computational complexity of RS. Copyright © 2015 John Wiley & Sons, Ltd.

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KEY WORDS: Linked Data; recommender systems; systematic review; web of data

1. INTRODUCTION

The increasing amount of heterogeneous information available on the Web has led to the difficulty in recommending relevant items that meet the requirements of end users. It has attracted the attention of researchers and has become an interesting research area from the development of the first *recommender systems* (RS) in the mid-1990s [1–3]. In fact, the interest in this area remains high because of the abundance of practical applications that help users to deal with different kinds of information [4].

Nowadays, RS are increasingly common in many application domains, as they use analytic technologies to suggest different items or topics that can be interesting to an end user. However, one of the biggest challenges in these systems is to generate recommendations from the large amount of heterogeneous data that can be extracted from the items. Accordingly, some RS have evolved to exploit the knowledge associated to the relationships between data of items and data obtained from different existing sources [5]. This evolution has been possible, thanks to the rise of the Web

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supported by a set of best practices for publishing and connecting structured data on the Web known as *Linked Data* [6].

Linked Data principles have lead to semantically interlink and connect different resources at data level regardless of the structure, authoring, location, and so on. Data published on the Web using Linked Data have resulted in a global data space called the Web of Data. Moreover, thanks to the efforts of the scientific community and the W3C Linked Open Data (LOD) project[‡], more and more data have been published on the Web of Data, helping its growth and evolution.

This work summarizes the state of the art of RS that make use of the structured data published as Linked Data on the Web. We undertook a systematic literature review, which is a form of secondary study that uses a well-defined methodology to identify, analyze, and interpret all available evidences related to specific research questions in a way that is unbiased and (to a degree) repeatable [7, 8]. We considered the most relevant problems that RS intended to solve, the way in which studies addressed these problems using Linked Data, their contributions, application domains, and evaluation techniques that they applied to assess their recommendations. Analyzing these aspects, we deduced current limitations and possible directions of future research. Unlike other works reporting the state of the art in RS [4, 9–11], our systematic literature review is the first to study RS that obtain information from Linked Data in order to generate recommendations.

The remainder of this paper is structured as follows. Section 2 provides a background information about Linked Data and RS. Section 3 summarizes the methodology and defines objectives and research questions. Section 4 outlines the results of the review organized according to each research question defined in Section 3. Section 5 discusses the results as well as the limitations of our systematic literature review. Section 6 contains the conclusions and future work. Finally, we list the selected papers in Appendix A.

2. BACKGROUND

2.1. *Linked Data*

In 1994, Tim Berners-Lee[§] uncovered the need of introducing semantics into the Web to extend its capabilities and to publish structured data on it, which became known as *Semantic Web*. The set of good practices or principles for publishing and linking structured data on the Web is known as Linked Data. While the Semantic Web is the goal, Linked Data provides the means to make it a reality [6]. The set of Linked Data principles are as follows:

- Use URI (uniform resource identifiers) as names for things.
- Use HTTP (Hypertext Transfer Protocol) URIs, so that people can look up those names.
- Use of standard mechanisms to provide useful information when someone looks up a URI, for example, RDF (Resource Description Framework) to represent data as graphs and SPARQL (SPARQL Protocol and RDF Query Language) to query Linked Data.
- Include links to other URIs, so that they can discover more things.

The main benefit of using Linked Data as a source for generating recommendations is the large amount of available concepts and the relationships between them that can be used to infer relations more effectively in comparison to derive the same kind of relationships from text [12]. As Linked Data information is machine-readable, it is possible to query datasets on a fine-grained level in order to collect information without having to take manual actions; therefore, information is explicitly represented, which allows for applying reasoning techniques when querying datasets and making implicit knowledge explicit.

2.2. *Recommender systems*

RS are software tools and techniques that provide suggestions of items to a user. These items can belong to different categories or types, for example, songs, places, news, books, films, and events.

[‡]<http://www.w3.org/wiki/SweoIG/TaskForces/CommunityProjects/LinkingOpenData>

[§]<http://www.w3.org/Talks/WWW94Tim>

According to Adomavicius and Tuzhilin [4], the roots of RS can be traced back to the works in cognitive science, approximation theory, information retrieval, forecasting theories, management science, and consumer choice modeling in marketing.

Nowadays, RS are focused on the recommendation problem of guiding users in a personalized way to interesting items in a large space of possible options [10]. Typically, RS are classified as content based, collaborative filtering, knowledge based, and hybrid [5].

Content-based RS make suggestions that take into account the ratings that users give to items according to their preferences and the content of the items (e.g., extracted keywords, title, pixels, and disk space) [10]. Collaborative-filtering RS generate recommendations of items to a user taking into account ratings that users with similar preferences have given to these items [13]. Knowledge-based RS infer and analyze similarities between user requirements and features of items described in a knowledge base that models users and items according to a specific application domain [14]. Hybrid RS combine one or more of the aforementioned techniques in order to improve recommendations.

With the evolution of the Web toward a global space of connected and structured data, a new kind of knowledge-based RS has emerged known as Linked Data-based RS. This kind of RS suggests items taking into account the knowledge of datasets published under the Linked Data principles. The systematic literature review presented in this paper is focused on this kind of RS.

3. RESEARCH METHODOLOGY

This work studies the state of the art in Linked Data-based RS. It follows the guidelines set out by Kitchenham and Charters [8] for systematic literature reviews in software engineering. These guidelines provide a verifiable method of summarizing existing approaches as well as identifying challenges and future directions in the current research. Figure 1 presents the protocol for our systematic literature review.

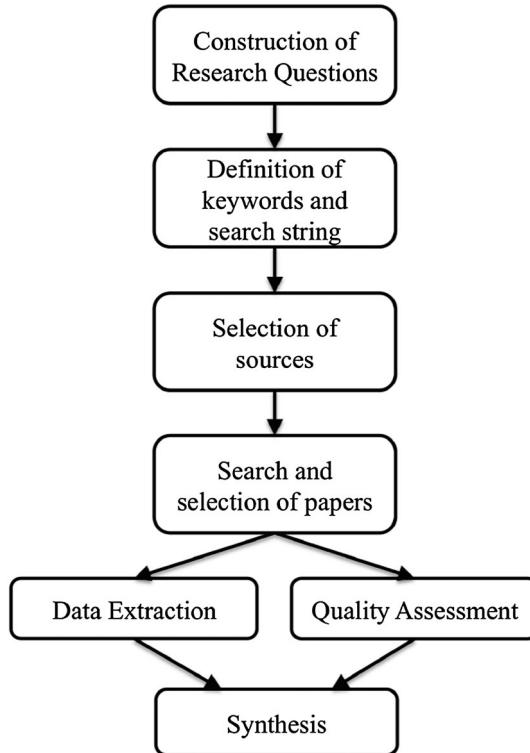


Figure 1. Systematic literature review at a glance.

The protocol is defined in order to setup the steps to conduct the systematic literature review. In our work, it was developed by the first and second authors, while the third and fourth authors validated it.

3.1. Construction of research questions, definition of keywords and search string, and selection of sources

The goal of our systematic literature review is to understand how the implicit knowledge, stored in Linked Data datasets and represented as concepts and relations between them, can be exploited to make recommendations. Accordingly, we have defined the following research questions:

RQ1 What studies present RS based on Linked Data?

RQ2 What challenges and problems have been faced by researchers in this area?

RQ3 What contributions have already been proposed (e.g., algorithms, frameworks, and engines)?

RQ4 How is Linked Data used to provide recommendations?

RQ5 What application domains have been considered?

RQ6 What criteria and techniques are used for evaluation?

RQ7 Which directions are the most promising for future research?

Afterwards, a preliminary set of keywords was defined: *{Linked Data, Recommender system}*. This set was then extended by searching for synonyms in order to obtain the final set of keywords used to define a search string. The search string is the query to look for papers in a set of online digital libraries. In this work, the search string that we defined is as follows:

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("semantic web" OR "linked data" OR "web of data" OR "linked open data") AND (recommendation OR "recommender system" OR "recommendation system" OR "semantic recommendation" OR "semantic recommender").
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Furthermore, we selected seven scientific digital libraries that represent primary sources for computer science research publications as can be seen in Table I. Other sources like DBLP, CiteSeer, and Google Scholar were not considered as they mainly index data from the primary sources.

3.2. Search and selection

The studies selected in this systematic literature review were identified from the selected sources during March 2014. In Table II, a set of inclusion/exclusion criteria were defined in order to determine whether or not a study should be included.

3.3. Quality assessment, data extraction, and synthesis

We have defined a set of quality criteria that are listed in the checklist provided in Table III. Quality for each question is typically scored with values 1, 0.5, and 0, in order to represent the answers 'yes', 'partly', and 'no'.

First and second authors evaluated the selected studies using this checklist. To do this, the total set of selected papers was split into two disjoint subsets, and each author selected only one of these

Table I. Sources selected for the search process.

Source	URL
IEEEExplore	http://ieeexplore.ieee.org
SpringerLink	http://link.springer.com
Scopus	http://www.scopus.com
ACM Digital Library	http://dl.acm.org
Science Direct	http://www.sciencedirect.com
ISI Web of Knowledge	http://apps.webofknowledge.com
Wiley Online Library	http://onlinelibrary.wiley.com

Table II. Inclusion and exclusion criteria.

Inclusion criteria
Papers presenting recommender systems (RS) using Linked Data to provide recommendations.
Papers addressing exploratory search systems using Linked Data. Exploratory search refers to cognitive consuming search such as learning or topic investigation. Exploratory search systems also recommend relevant topics or concepts, although the key difference with respect to RS is that they still require an input query (commonly a set of keywords).
Papers from conferences and journals.
Papers published from 2004 to 2014. Linked Data is a relative new technology; therefore, RS approaches exploiting it are also recent.
Only papers written in English language.
Short and workshop papers that fulfill the above criteria: we had no reason to believe that they would fail to provide sufficient levels of detail about their studies.
Exclusion criteria
Papers not addressing RS neither exploratory search systems.
Papers addressing RS or exploratory search systems that do not exploit Linked Data to produce recommendations.
Papers addressing similarity measures but not RS. Similarity is a broader topic than RS.
Papers that use Semantic Web techniques (e.g., rule-based or ontology-based reasoning) but not Linked Data.
Papers that report only abstracts or slides of presentations because of the lack of information.
Grey literature. We do not think that technical reports, unpublished studies, and PhD thesis would add much more information with respect to journal and conference papers.

subsets to evaluate the papers. After this evaluation, cross-checking of the assessment was done on arbitrary studies (about 30 % of selected papers) by the third author. Finally, an agreement on differences was reached by discussion.

Data extraction was done in parallel with the quality assessment. We split the set of included studies into two disjoint subsets. First and second authors performed the task on a subset, then the third author cross-checked a random sample of 30% of studies. The data extracted are presented in Table IV.

The synthesis step is based on the methodology for thematic synthesis described by Cruzes and Dybå [15]. This methodology defines codes as descriptive labels applied to segments of text from each study. We defined an initial set of codes based on research questions, and subsequently, we performed a second coding with more precise codes, which were closer to the content of selected papers. The coding was performed by first and second authors: each of them addressed a subset of the papers as for data extraction and quality assessment, because it was done in parallel with them. Then, the third author performed again the coding on a random sample of 30% of papers for cross-checking; afterwards, disagreements were solved by discussion.

4. RESULTS

This section summarizes the relevant information found in the selected studies in order to answer the proposed research questions. A further discussion and analysis of these results are addressed in Section 5.

4.1. Included studies

RQ1 regards the studies that present RS based on Linked Data. We retrieved 69 papers to include in the systematic literature review, corresponding to 52 unique primary studies (a study is a unique research work that can include one or more papers). These studies were published in conferences, workshops, and journals between 2004 and 2014. The criteria for deciding the most significant

Table III. Quality assessment checklist.

Question	Score
Q1. Did the study clearly describe the challenges and problems that is addressing?	yes / partly / no (1 / 0.5 / 0)
Q2. Did the study review the related work for the problem?	yes / partly / no (1 / 0.5 / 0)
Q3. Did the study discuss related issues and compare with the alternatives?	yes / partly / no (1 / 0.5 / 0)
Q4. Did the study recommend the further continuous research?	yes / partly / no (1 / 0.5 / 0)
Did the study describe the components or architecture of the proposed recommender system?	yes / partly / no (1 / 0.5 / 0)
Q5. Did the study describe the components or architecture of the proposed recommender system?	yes / partly / no (1 / 0.5 / 0)
Q6. Did the study provide empirical results?	<ul style="list-style-type: none"> – The study provided an implementation of its work with an empirical evaluation and it was used in real applications, e.g., by other services (1) – The study provided an implementation of its work and an empirical evaluation but was not referred or used in other studies/applications (0.75) – The study provided an implementation only (0.5) – The study did not provide any implementation but it was referred by other works as a base on which start (0.25) – The study did not provide any implementation and was not referred by other works (0)
Q7. Did the study provides a clear description of the context in which the research was carried out?	yes / partly / no (1 / 0.5 / 0)
Q8. Did the study presents a clear statement of findings?	yes / partly / no (1 / 0.5 / 0)

paper for each study were completeness and publication year. The final set of selected papers and corresponding studies can be found in Appendix A.

With regard to the quality assessment, *journals* and *conference* studies have better quality than *workshop* studies as shown in Figure 2. Conference studies have the biggest spread, while journal studies, the lowest. In any case, the quality score is higher than 0.5 for all paper types, that is, rather good according to the quality criteria defined in Section 3.3.

4.2. Research problems

In order to address RQ2, we summarize the main problems involved in the studies considered and regarding the production of accurate recommendations. Table V lists these problems according to the number of studies in which they occurred. The number of studies represents the occurrence of each problem in the selected studies, which may be addressed in more than one study. The same applies for the rest of the results reported in this section.

In the following, we describe each item of Table V:

Lack of semantic information It was the most frequent problem in the selected studies, and it concerns the need for exploiting the rich semantics of information about items. Possible causes of this problem are as follows:

- Data about items are unstructured.
- A categorization of the items is needed.

Table IV. Data extraction form.

Data field	Description	Research question
ID	—	—
Title	—	—
Authors	—	—
Year of publication	—	—
Year of conference	—	—
Volume	—	—
Issue	—	—
Location	—	—
Proceeding title	—	—
ISBN	—	—
Publisher	—	—
Examiner	Name of person who performed data extraction	—
Publication source	—	—
Context	Environment in which study was conducted: industry, academic, government	—
Population	Study participants: students, academics, practitioners, etc.	—
Aims	Goals of the study (in our opinion when not clearly reported by authors)	—
Research problem	—	RQ2
Application domain	—	RQ5
Contributions	—	RQ3
Criteria and techniques for evaluation	—	RQ6
Findings	—	—
Limitations	—	RQ7
Future work	—	RQ7
Notes	—	—
Other information	—	—

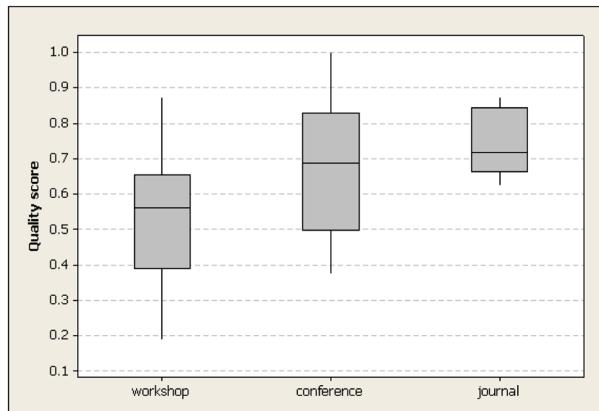


Figure 2. Quality score for different types of study.

- It is necessary to find relationships to link items.
- Social information is lacking.
- It is necessary to acquire content-descriptive metadata.
- Similarity measures that take into account semantic information are needed.

Complexity of information about items It is related to the complexity of information because of noisy metadata about features of items. Other causes for this problem are semantic heterogeneity and distribution of resources. The latter can impact on maintenance of the knowledge bases and can also decrease the accuracy of recommendations.

Table V. Distribution of studies according to the problems they addressed.

Problems	Number of studies
Lack of semantic information	13
Complexity of information about items	12
User dependency	8
Cold-start	6
Data quality	6
Computational complexity	5
Data sparsity	5
Domain dependency or specific and limited domain	4
Other problems	2

Table VI. Distribution of studies according to the contributions provided.

Contribution	Number of study
Algorithms	27
Similarity measures	12
Ontologies	8
Information aggregation or enrichment	8
Others	16

User dependency In a number of cases, RS require users to perform manual operations to acquire information about their profiles and interests. Such operations can be user feedback, ratings, filtering, attaching content-descriptive metadata, and semantic annotation of items.

Cold-start It is a well-known problem found mainly on RS based on collaborative-filtering approaches. Cold-start is a situation in which there are not enough ratings for items in order to generate recommendations.

Data quality This problem occurs when the knowledge base used to acquire information for providing recommendations is not reliable. Problems affecting data quality can range from poor reliability (e.g., wrong links between concepts or incorrect representations) to poor quality of recommended items.

Computational complexity It is related to the high computational demand that RS require to produce recommendations because of the large amount of data about items.

Data sparsity This is related to the lack of information about users or items and generates low density of significant data or connections.

Domain dependency It occurs when recommendations are only useful for items in a specific and limited domain without taking into account data that can be obtained from other related domains.

Other problems They include the need for recommending relevant and yet unknown items and the overspecialization of RS.

4.3. Contributions

In order to address RQ3, we classified the contributions provided by each study. Table VI shows the different kind of contributions and the number of studies in which they occurred (each study possibly reports more than one contribution).

The two main contributions are the definition or extension of a similarity measure and the definition or extension of an ontology, accounting for 12 and eight studies respectively. Algorithms are also addressed by 27 studies in total. Finally, information aggregation or enrichment and various other contributions account for eight and 16 studies, respectively. In the following, we describe each item of Table VI:

Algorithms Most of the selected studies proposed new algorithms or extensions of algorithms existing in the literature. In particular, four categories emerged: defining of a new algorithm,

adapting an algorithm to Linked Data, combining of algorithms to obtain a new hybrid algorithm, and extending of an existing algorithm. The definition of a new algorithm was the most frequent in 15 studies, while the adaptation of an algorithm to Linked Data, the combination of algorithms to obtain a new hybrid algorithm, and the extension to an algorithm each account for 4 studies. Furthermore, we can group algorithms into two classes:

- Graph-based algorithms, which compute relevance scores for items represented as nodes in a graph. A number of algorithms in this category are (*i*) the weight spreading activation algorithm, which propagates the initial score of a source node through its weighted edges; (*ii*) algorithms that update the scores of its linked nodes; (*iii*) algorithms that explore concepts and relations defined in an RDF graph; (*iv*) topic-based algorithms, which find similar items belonging to the same categories of an initial concept; and (*v*) path-based algorithms to find semantic paths between documents in the RDF graph.
- Algorithms to produce recommendations based on statistical information techniques applied to Linked Data such as support vector machine (SVM), latent Dirichlet allocation (LDA), random indexing (RI), and scaling methods. SVM analyzes and recognizes patterns in RDF triples; LDA is based on the co-occurrence of terms; RI uses distributional statistics to generate high-dimensional vector spaces; and scaling methods take into account the probability that an item could be selected based on its popularity (the number of entities is directly connected with the node). In addition, some algorithms define item-user matrices to compute semantic similarity based on path-lengths.

Similarity measures The selected studies applied a variety of similarity measures. These include pairwise cosine function for vector similarity computation between items, feature-based similarity to evaluate semantic distance on different datasets, rating-based similarity to compute the popularity of items among users, semantic relatedness defined by vocabulary meta-descriptions, content similarity that exploits lexical features, expressivity closeness based on the language constructs adopted, distributional relatedness derived from vocabulary usage, and topic-based similarity that captures the relatedness between items based on the categories they belong to.

Ontologies A number of studies proposed ontologies to assist or improve the recommendation process. New ontologies were proposed to facilitate the process of integration of datasets from a number of domains in order to make RS more flexible to changes, while a combination of existing ontologies described different types of entities such as users and items. Furthermore, it was found that reusing existing ontologies or vocabularies enable interoperability. Ontologies are also used to represent semantic distances, their explanations, user preferences, and item contents. A number of ontologies that are used in selected studies for these purposes are FOAF (Friend Of A Friend), SIOC (Semantically-Interlinked Online Communities), Resource List Ontology and Bibliographic ontology.

Information aggregation or enrichment This refers to the contributions about the aggregation of data to item collections and enrichment of existing ontologies or vocabularies. This is useful, for example, to obtain descriptive information about items and find entities in datasets in order to infer links between them. One contribution of this type is the aggregation of information from a specific domain when items have to be enriched with knowledge contained only on specialized datasets, another is the enrichment databases of RS with shared vocabularies.

Others Other contributions include the integration of other techniques such as opinion aggregators, exploitation of trust in web-based social networks to create predictive RS, and the use of social-based algorithms to improve the performance of the RS.

4.4. Use of Linked Data

Another interesting aspect that we studied was the use of Linked Data in RS, as underlined by RQ4. We classified the selected studies according to the way they used Linked Data to produce recommendations and grouped them into the following:

Linked Data driven RS that rely on the knowledge of the Linked Data to provide recommendations. For example, RS that calculate a semantic similarity based on diverse relationships that can

Table VII. Distribution of studies according to the use of Linked Data.

Category	Number of studies
Linked Data driven	37
Hybrid	29
Hybrid and Linked Data driven	21
Linked Data driven only	13
Representation only	10
Hybrid only	6
Exploratory search	4
Exploratory search and Linked Data driven	4
Exploratory search only	0

be found between concepts of Linked Data datasets and are related to features or descriptions of items. Such relationships can be paths, links, or shared topics among a set of items. This category can also include RS that use other techniques applied on data obtained from Linked Data datasets, for example, weight spreading activation, vector space model (VSM), SVM, LDA, and random indexing.

Hybrid RS that exploit Linked Data to perform some operations that can be used or not used to provide recommendations. This means that hybrid RS include Linked Data driven RS, which use recommendation techniques that rely on Linked Data, and RS that use Linked Data in other operations (not necessarily for recommending) that can be preliminary to the recommendation process (e.g., to aggregate more information from other datasets, to describe user profiles, or to annotate raw data in order to extract information to be integrated and used for recommending).

Representation only RS in this category exploit the RDF format to represent data and use at least one vocabulary or ontology to express the underlying semantics. However, no information is extracted from other dataset, and Linked Data are not used to provide recommendations. An example is an RS that represents the information about the users according to FOAF vocabulary but does not exploit Linked Data for other operations.

Exploratory search These systems are not RS, but their main duty is to assist users to explore knowledge and to suggest relevant to a topic or concept. Exploratory search systems and RS use Linked Data in a very similar way, although the key difference is that exploratory search systems still require an explicit input query (commonly a set of keywords). Additionally, users in these systems are not only interested in finding items but also in learning, discovering, and understanding novel knowledge on complex or unknown topics [16].

Each study may be assigned to more than one category; that is, it can be both Linked Data driven and hybrid, or both exploratory search and Linked Data driven. The only exception is for the representation-only category, in which studies cannot belong to other categories.

Table VII shows that most of the studies considered are Linked Data driven, and roughly 60% of them are also hybrid. Only 20% of hybrid studies were hybrid only, while the rest are also Linked Data driven. Moreover, 10 studies are representation only and just four exploratory search systems were included in the systematic literature review. All of the exploratory search studies are also Linked Data driven. This finding is consistent with the focus of the systematic literature review, which is on RS using Linked Data. It is worth noting that exploratory search is a broader topic; in this paper, we only consider the exploratory systems that recommend concepts to users.

The two most interesting categories are Linked Data driven and hybrid. Figure 3 shows the different techniques used by the studies in the first category to provide recommendations. The majority of them rely on datasets or on a similarity measure (about 43% and 35%, respectively), while the remaining 22% adapt natural language processing or content-based techniques or exploit reasoning.

Instead, Figure 4 illustrates the techniques that hybrid studies use together with Linked Data to provide recommendations. Most of them are natural language processing or collaborative-filtering methods (accounting for slightly less than 40% and about 35%, respectively), and also reasoning or social networks are exploited in some cases.

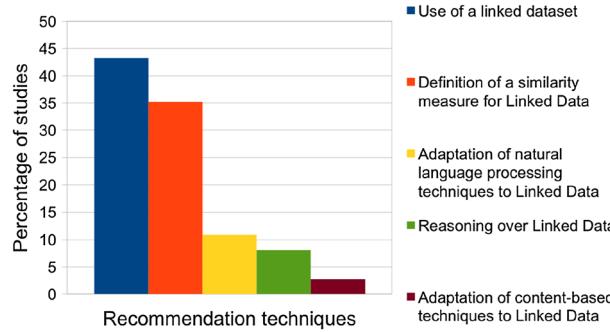


Figure 3. Distribution of Linked Data driven studies according to the recommendation techniques that they exploit (percentages refer to the total number of Linked Data-driven studies).

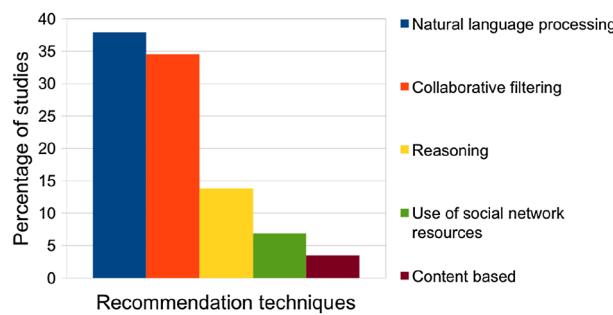


Figure 4. Distribution of hybrid studies according to the recommendation techniques that they exploit (percentages refer to the total number of hybrid studies).

Table VIII. Distribution of studies according to the Linked Data (LD) datasets on which they rely.

Dataset	Number of studies				
	General	LD driven	Hybrid	Hybrid and LD driven	LD driven only
DBpedia	31	28	20	16	12
Freebase	6	6	5	5	1
YAGO	4	3	3	2	1
Wordnet	4	2	3	2	0
DBLP	3	3	3	3	0
Dataset independent	3	3	3	3	0
LinkedMDB	3	3	3	3	0
Geonames	2	1	2	1	0
MusicBrainz	2	1	2	1	0
mySpace	2	2	2	2	0
ACM	1	1	1	1	0
IEEE	1	1	1	1	0
Eventseer2RDF	1	1	1	1	0
LinkedUp	1	1	0	0	1
mEducator	1	1	0	0	1
LinkedGeoData	1	0	1	0	0
LODE	1	1	1	1	0

In addition, we studied which datasets are used and the outcome is presented in Table VIII. It shows how many studies use a dataset overall and also considers the study category. It is possible to notice that DBpedia is used much more than the others. In fact, it is the biggest dataset, and it is the most curated.

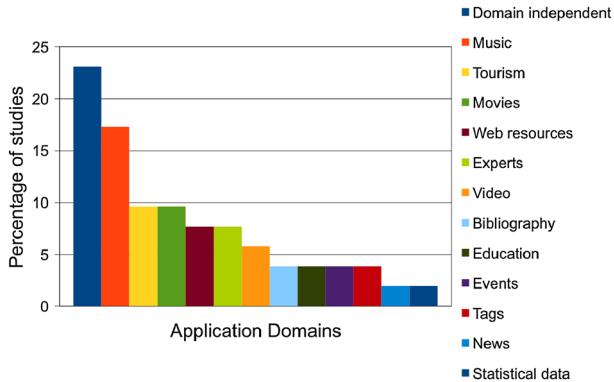


Figure 5. Distribution of studies according to the application domain.

Furthermore, it contains information about many different domains. Other commonly used datasets are Freebase, YAGO, and Wordnet, but the latter is used in just half of the cases by Linked Data-driven studies. In fact, it is also used with natural language processing techniques. On the contrary, the other datasets are used in most cases by Linked Data driven studies and often by studies which are both Linked Data driven and hybrid.

4.5. Application domains

Figure 5 illustrates the application domains considered by the studies selected for the systematic literature review. Most of the studies (about 23%) are not limited to any particular domain and can be used to recommend different kinds of items. Instead, an often occurring domain is music, which represents 17% and is followed by tourism and movies, accounting for roughly 10% each. Then there are web resources, expert recommendations, and video, with between 5% and 7% each, and a number of other domains are considered by the remaining 10% of the studies.

4.6. Evaluation techniques

RQ6 concerns RS evaluation, so we also dealt with this aspect. It is important to note that we focus on RS evaluation; thus, GUI evaluation is not considered, although some of the studies addressed it. RS are commonly evaluated according to their computational complexity and accuracy [17]. The former measures the execution time required to produce recommendations, which depends on the complexity of the algorithms used as well as the runtime of third-party systems needed to produce recommendations. The latter is the capacity of the RS to satisfy the individual user's need for information, and it can be evaluated by means of two techniques: user studies and comparison with similar methods. In this subsection, we detail both of them.

User studies involve users in order to compare recommendations generated by RS with the users' judgements or ratings. In these techniques, the most frequent measures are the following:

- Precision and recall, which evaluate the relevance of an RS taking into account the number of retrieved items, the number of items that evaluators considered as relevant, and the total number of available items.
- User ratings, which are techniques in which a list with results from different RS are presented to users who rate the lists according to their personal criteria [17].
- Ranking quality, which takes into account the retrieval correctness. The latter assigns an output ranking, a performance score based upon the available reference relevance judgments [18]. Common metrics to measure the ranking quality are the normalized discounted cumulated gain, average position, and presence.
- Unexpectedness of a concept suggestion, which is the degree of novelty of a recommendation for the evaluator.

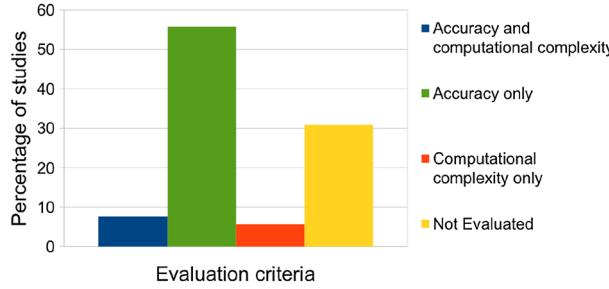


Figure 6. Distribution of studies according to the evaluation criteria (percentages refer to total number of studies).

Table IX. Distribution of studies according to the evaluation techniques.

Type	Technique	Number of papers
User studies	Precision and recall	18
	User ratings	9
	Ranking quality	3
	Unexpectedness	3
Comparison with similar methods	Precision and recall	5
	MAE and RMSE	3
Computational complexity	Execution time	7

MAE, mean absolute error; RMSE, root mean squared error.

In the case of comparisons with similar methods, recommendations generated by a specific RS are compared with well-known similar approaches. In the following, we mention the two main types:

- Precision and recall are measured, but in this case, items recommended by a well-known approach are considered as relevant.
- Mean absolute error (MAE) and root mean squared error (RMSE) are metrics to measure the predictive accuracy of an RS. MAE calculates the average absolute deviation between predicted similarities and similarity values in the real data set, while RMSE pays more attention to large errors [19].

Figure 6 shows the main evaluation techniques found in the selected studies, as well as their classification and their occurrence in these studies. Studies that provided an evaluation accounted for about 70% of the studies included in the systematic literature review. Among these, roughly 55% only used an accuracy technique, while roughly 2% only evaluated the computational complexity, and slightly less than 8% considered both accuracy and computational complexity.

Table IX details the techniques used in the studies included by considering the two types of accuracy evaluation and also computational complexity. The most frequent technique used to evaluate RS is the relevance measured with recall and precision metrics (used by 18 works in user studies and by about five in comparison with similar methods). We expected this result because these metrics are the ones most commonly deployed in information retrieval approaches. Other widely used techniques are user ratings, accounting for nine studies, and execution time, which is exploited by seven studies.

4.7. Future work

RQ7 is related to directions for future research. To address this, we summarized the future work that the selected studies proposed in order to extend or improve their approaches. Specifically, about 67% of studies included in the systematic literature review present diverse proposals for future work. Table X lists the most important, indicating for each one the number of studies in which it was mentioned. A deeper analysis of these results and a discussion of possible directions is presented in Section 5.

In the following, we provide a brief description of each item reported in Table X:

Table X. Distribution of studies according to the future work they propose.

Future work	Number of studies
Personalization of recommendations	8
Use more datasets	8
Create hybrid recommender systems	7
Similarity measures	4
Find more semantic relationships (item-user and item-item)	3
Other proposal for future work	3
Consider other domains	2

Personalization of recommendations The idea is to know to what extent personalization can improve recommendations without requiring user profile information or user intervention for manual operations (feedback, filtering, annotation, etc.).

Use more datasets It means to increase the range of data to annotate or match items to be recommended. It can also be useful to explore new domains because of the use of other datasets which can be from diverse domains.

Create hybrid RS This refer to exploring new ways to combine diverse recommendation techniques for creating hybrid approaches and improving the relevancy and quality of recommendations.

Similarity measures It is the creation of new similarity measures or the improvement of existing ones.

Find more semantic relationships It is the possibility of finding more semantic relationships between items and between users and items. It is considered by three studies.

Consider other domains Although domain dependency is one of the problems found in various studies, only two studies took into account exploring new application domains for providing recommendations.

Other proposal for future work This group includes applications in real life contexts, algorithms for categorization of recommendations, improving performance of algorithms, and the study of disambiguation techniques.

4.8. Limitations

The limitations reported in the selected studies are also related to RQ7 as these can help us to uncover the open issues in RS based on Linked Data and their relationships with proposals of future work. They are grouped into four main types: datasets, manual operations, personalization, and computational complexity. We detail each of them in the following:

Datasets This type describes limitations of RS due to the datasets used.

- A number of studies required a local copy of the entire dataset in a local server in order to reduce the runtime to produce recommendations. This had to be done as sometimes public datasets offer limited results, restricted access, and high timeout.
- Sometimes data had to be manually curated because of the poor reliability of public datasets.
- A number of RS are limited to the use of only one dataset. This can restrict the knowledge to which the RS can have access, avoiding data from diverse sources and domains being obtained.

Manual Operations It means that RS needed the user to perform manual operations in order to produce recommendations. Among these operations, we found:

- RS requiring manual selection of relevant concepts according to a specific application domain or interests. This is a difficult and tedious task considering the large amount of data that a typical Linked Data dataset can contain.
- RS that did not rank their results, so final users are faced with no priority in the recommendation.

Personalization It is about producing recommendations according to the user profile or some personal features.

Computational complexity RS still need to improve the performance because of high computational demand to analyze large amounts of items and information stored into datasets. Another problem is the poor performance of public endpoints to access them.

5. DISCUSSION

In the first part of this section, we present a discussion of the results considering each research question, while in the second part, we mention the limitations of our systematic literature review.

5.1. Specific research questions

This subsection discusses the research questions addressed in this systematic literature review according to the results reported in Section 4.

RQ1 is a general question regarding the studies that describe RS based on Linked Data. To provide an answer, we have followed the steps described in the protocol presented in Section 3 in order to search and select studies in this area. Firstly, we retrieved a total number of 7873 papers (including those duplicated) from scientific digital libraries. After each author filtered papers by title and abstract, we discussed disagreements, and we reach consensus on a final set of 69 papers to include in our study, which correspond to 52 unique studies.

RQ2 deals with research problems in the RS domain that researchers intended to solve by proposing approaches based on Linked Data. We found that the lack of semantic information and its complexity were the most notorious problems in RS.

Lack of semantics regards the need for rich semantic information about items. This is the main reason to devise novel strategies to represent items and user profiles using diverse semantic techniques exploiting several knowledge sources from the Linked Data cloud.

The complexity and heterogeneity of information and the subsequent cost of maintenance of knowledge bases make Linked Data a suitable solution that uses publicly available knowledge bases that are continuously growing and maintained by third parties. However, this poses new challenges, for example, the need for mechanisms to assure the reliability of these knowledge bases that are used to describe user profiles and items and to generate recommendations.

Domain dependency is another problem that has been also addressed by using Linked Data because it allows the possibility to exploit information from different datasets that can be domain-independent or belong to diverse domains. In fact this is one reason why the most used dataset is DBpedia as it is the most generic dataset that can be used for cross-domain RS. Nonetheless, some studies still report this problem as future work.

Computational complexity is a question that has not been widely addressed in the studies considered in this systematic literature review and remains as an open issue because most of the studies have concentrated only on semantic enrichment of items and inclusion of datasets in Linked Data cloud. Computational complexity needs to be addressed more because in RS not only accuracy is important but also scalability and responsiveness. For example, this problem can be critical in RS for mobile scenarios where users demand fast response times.

Other problems such as usability, cold-start, data quality, and data sparsity have been addressed by combining with Linked Data various techniques based on natural language processing, reasoning or social network resources, and creating hybrid RS that exploit both collaborative filtering and content-based approaches.

RQ3 inquires about the contributions proposed in RS based on Linked Data. The analysis showed that the majority of studies are focused not only on providing new algorithms but also on defining or extending a similarity measure of an ontology. Furthermore, adaptation, combination, or extension to algorithms is quite often addressed together with information aggregation

or enrichment. Accordingly, we found that Linked Data can be used in RS for several purposes such as the following:

- Defining different similarity functions between items or users by exploiting the large data available in the Linked Data cloud and the vast relationships already established such as properties or context-based categories. In this way, it is possible to extract semantic information from textual descriptions or other textual properties about the items in order to find semantic similarities based on the information stored in interlinked vocabularies of Linked Data. This can be useful in RS based on collaborative filtering to improve the neighborhood formation in user-to-user or item-to-item.
- Generating serendipitous recommendations, for example, to recommend items that are not part of the users' personal data cloud, that is, suggest new, possibly unknown items, to the user; or to guide users in the process of the exploration of the search space giving the possibility for serendipitous discovery of unknown information (for exploratory search systems).
- Offering the explanation of the recommendations given to the users by following the linked-data paths among the recommended items. In this way, users can understand the relationship between the recommended items and why these items were recommended.
- Domain-independency when creating RS as it is possible to access data from Linked Data datasets from different domains.
- Enrichment of information sources such as databases, repositories, and registries with information obtained from dataset in Linked Data cloud which manage huge amounts of data. It offers the possibility to enrich graphs representing users and/or items with new properties in order to improve graph-based recommendation algorithms. Additionally, it helps to mitigate the new-user, new-item, and sparsity problems.
- Annotating items and users with information from multiple sources facilitate RS to suggest items from different sources without changing their inner recommendation algorithms. Using such a semantic-based knowledge representation, recommendation algorithms can be designed independently from the domain of discourse.
- Obtaining hierarchical representation of items because the topic distribution that some datasets in Linked Data cloud offer. In this way, RS can base their recommendation on the exploration of items belonging to similar categories.

RQ4 regards the diverse ways in which Linked Data is used to provide recommendations. First of all, we classified the studies according to the way they exploited Linked Data. As reported in Section 4, four categories were identified: *Linked Data driven RS* rely mainly on Linked Data to perform their tasks, *hybrid RS* use Linked Data and also other techniques, *representation-only RS* do not provide Linked Data-based recommendations but use Linked Data for representing data based on RDF, and finally *exploratory search systems* that are not RS but may help users to find concepts or topics and have some similar features to RS especially in the use of Linked Data.

Table XI describes each category including the most important studies that adopted these strategies, as well as their advantages and disadvantages. The numbers of the studies corresponds to the identifiers in Appendix A.

Most of the studies belong to the first category, and many belong to both the first and the second category. These two categories are also the most interesting as they include RS to better exploit the advantages provided by Linked Data in order to reach best results. We also studied techniques to provide recommendations relying on Linked Data and slightly less than half of Linked Data driven RS used a dataset, almost one third define a similarity measure for Linked Data, while others adapt natural language processing or content-based methods or use reasoning.

With reference to the techniques used together with Linked Data, we found that natural language processing and collaborative filtering are the most used (both account for about one

Table XI. Classification of Linked Data-based RS approaches.

Approach	Techniques	Advantages	Disadvantages
Linked Data driven	<ul style="list-style-type: none"> - <i>Graph based:</i> weight spreading activation (S17), semantic exploration in an RDF graph (S29, S10, S3, S9, S19), and projections (S23) - <i>Reasoning:</i> (S1, S51) - <i>Statistical:</i> Matrix item-user (S29, S35, S31, S13, S37, S10), Scaling methods (S29) and topic discovery (S2) - <i>Collaborative Filtering and Linked Data:</i> (S2, S4, S12, S25, S27, S3, S28, S26, S30, S35) - <i>Information aggregation and Linked Data:</i> opinions (S16), ratings (S19), and social tags (S32) - <i>Statistical methods and Linked Data:</i> Random Indexing (S10), VSM (S47, S31, S35), LDA (S35), Implicit feedback (S25), SVM (S13), Structure-based statistical semantics (S37) 	<ul style="list-style-type: none"> - Generating serendipitous recommendations - Offering explanations of the recommendations following the linked-data paths - Creating domain-independent RS - Exploiting hierarchical information about items to categorize recommendations 	<ul style="list-style-type: none"> - High cost of exploiting semantic features due to inconsistency of LD datasets - No personalization - No contextual information - High computational complexity - Need for manual operation - Need for dataset customization to address the computational complexity
Hybrid		<ul style="list-style-type: none"> - Overcoming the data sparsity problem - Allowing collaborative filtering RS to address the cold start problem 	<ul style="list-style-type: none"> - High computational complexity
Representation only	<ul style="list-style-type: none"> - Item/user information representation using RDF-based ontologies (S36, S38, S20, S40, S14, S15, S42, S46) 	<ul style="list-style-type: none"> - Improving scalability and reusability of ontologies - Easing data integration - Enabling complex queries 	<ul style="list-style-type: none"> - Difficult to reuse the already available knowledge in the Linked Data Cloud
Explorative search	<ul style="list-style-type: none"> - Set nodes and associated lists (S49, S39, S34) - Spreading activation to typed graphs and graph sampling technique (S11) 	<ul style="list-style-type: none"> - Enabling self-explanation of the recommendations 	<ul style="list-style-type: none"> - No automation of the recommendation because explorative search approaches require frequent interaction with the user

third of hybrid RS) as they intended to provide personalized suggestions of items tailored to the preferences of individual users.

Other techniques are less common (less than 15%), and they are reasoning, use of social network resources, and content-based methods. Reasoning has not been widely used as its quality is still insufficient, and its coverage is not broad enough at the level of system components and knowledge elements [20]. Therefore, one solution is to develop RS based on reasoning-oriented natural language processing enriched with multilingual sources and able to support knowledge sources generated largely by people as Linked Data datasets.

As for the datasets used in the selected studies, we found that DBpedia is the most used Linked Data dataset. This is because DBpedia is a generic dataset and most of the studies are domain-independent that need to be evaluated in diverse scenarios. DBpedia is one of the biggest datasets that is frequently updated as it obtains data from Wikipedia that continuously grows into one of the central knowledge sources [21]. It makes Dbpedia multimodal and suitable for RS that need to be domain-independent and for knowledge-based RS where complexity and cost of maintenance of the knowledge base is high. However for RS of a single domain, it is better to use specific datasets but always implementing a linking interface with generic datasets in order to resolve ambiguities or to exploit unknown semantic relationships.

RQ5 concerns the application domains considered by RS based on Linked Data so far. We identified 12 domains, but we found that most of the RS are domain-independent (slightly more than one fifth of the studies). This is because most of the proposed recommendation algorithms can be applied in diverse domains by only changing the dataset or taking only a portion of it in order to obtain the data to generate the recommendations.

However, we also note that items of music, tourism, and movies are the most recommended as these belong to common domains in which there is a large amount of data and state-of-the-art datasets available, which allow the researchers to compare their results with several works developed in the community.

Accordingly, in a number of cases, the domain impacts also on datasets because they require a reduction of information; that is, only a subset of concepts is considered, which requires offline processing and more effort to maintain the dataset even if it improves the performance. For example, Passant developed RS named *dbrec* [22], which required to manually extract a subset of the data of DBpedia related with bands and musical artists.

RQ6 regards the evaluation techniques used to study RS based on Linked Data. We classified them into two types: accuracy and computational complexity. Accuracy evaluates recommendations according to their relevance for final users, while computational complexity measures the execution time required to produce them.

With regard to accuracy, our results demonstrate that researchers are more interested in evaluations made by final users than in comparisons with similar methods. This result was expected because usefulness of recommendations depends more on final user preferences than on comparing with similar approaches where evaluation may be biased as researchers must trust the results obtained. Therefore, future methodologies of evaluation should be user-centered in order to assure the quality of the results of RS.

Additionally as expected, most of the selected studies were more likely to evaluate their recommendations applying traditional methods of information retrieval such as precision and recall that are focused on percentages of true positives, false negatives, and false positives.

Interestingly, we found that few works evaluated the computational complexity of RS, which is a critical factor specially for applications that need responses with short timeouts. Therefore, it is still an open issue considering that accessing Linked Data datasets in most cases is time consuming and requires that researchers download dumps of the datasets to access them in local repositories.

RQ7 aimed to uncover the most promising directions for future research on RS based on Linked Data. To address this issue, we have reported not only future works but also limitations of the selected studies.

Section 4.7 summarized the future work reported in the selected studies. We found that the most frequently future works were the personalization of recommendations, the use of more datasets, and the creation of hybrid RS.

The lack of personalization of recommendations is still a common drawback in Linked Data-based RS. It concerns the fact that different users obtain the same set of results with the same input parameters. To solve this drawback, some RS need explicit feed back from users in order to differentiate the results based on information about the user's profile (e.g., browsing history and favorite music genre).

However, these approaches force the user to perform extra work like rating items or building an exhaustive user profiles. Consequently, there is a need of non-invasive personalization approaches supported by Linked Data in order to obtain implicit information from the neighborhood relationships user-to-user, item-to-item, and user-to-item. These relationships can be inferred from the links between concepts of datasets in Linked Data cloud related with properties of items and users.

Using more datasets is needed in order to increase the base of knowledge to produce recommendations. As presented in Section 4.8, there are some limitations of the current Linked Data-based RS with regard to the use of Linked Data datasets such as restricted access, poor reliability, computational complexity, low coverage of languages, domain dependency, and the need for installing a local copy of the dataset. For this reason, it is important to investigate new ways to integrate different datasets in order to (*i*) extend the knowledge base allowing the RS to access to other datasets in case that the main dataset fails or the data are not reliable; (*ii*) create scalable RS because they can be adapted to other domains by only accessing to the appropriate dataset and (*iii*) improve the performance by selecting datasets with better response time.

The creation of hybrid RS is not a new proposal, as could be seen in Section 4.4, combining diverse techniques of recommendation with Linked Data-based approaches is a frequent practice in the selected studies. However, we also found that it is still an open issue because it is necessary to investigate which combinations of techniques are more suitable for RS applied in diverse contexts. For example, combining Linked Data-based RS with social-based RS can be a good choice for applications that require information about the users and their interrelationships. In this way, RS can access information that sometimes is not available in Linked Data datasets such as items rating information, user profiles, and other social information.

The inclusion of user profile information (user profiling) is another aspect that is not widely considered in Linked Data recommender systems. The idea behind the user profiling is to obtain a meaningful concept-driven representation of user preferences in order to enable more precise specifications of user's preferences with less ambiguity. Therefore, this can be also useful to contribute to the personalization of Linked Data-based RS.

The automatic selection of the appropriate dataset according to the type of items or the application domain is another challenge that intend to improve the quality of recommendations. This dynamic process of selection can help the algorithms to choose the best strategy to find candidate items to be a recommender based on the implicit knowledge contained in Linked Data and the relationships with properties of items and users.

As a consequence, it is also important to study new similarity measures and techniques able to automatically combine information from different datasets and to deal with the diversity of data in these datasets. Furthermore, it can be possible to create a statistical models of user interests to overcome the topical diversity of rated items.

Finally, we found that there is still a need for building testbeds in order to allow for rigorous, transparent, and replicable testing and for studying new techniques (or adaptation of those existing) for evaluating the accuracy and computational complexity of RS based on Linked Data. This must also consider that Linked Data-based RS may have access to large amounts of information and that links among items can be unknown to the users. Additionally, large-scale RS should be also evaluated in terms of the ability to scale and provide recommendations with data coming from millions of users and/or items

5.2. Limitations of our systematic literature review

This section describes the main limitations we faced during our systematic literature review. Firstly, although some of selected papers were initially included because of their title or abstract, in the end they were excluded because we could not access them from our University.

Secondly, we only considered the most relevant paper for each study in order to calculate the frequency of problems, future work, contributions, and evaluation techniques. As a consequence, we could be biased, as some papers belonging to the same study may present a problem or contribution not reported in the most relevant paper.

Finally, we did not perform deep validation. Because of time issues, the majority of studies were read by one researcher, and cross-checking was performed only on about one third of the studies. Nonetheless, for some papers for which assessment was difficult, there was a discussion between the first three authors.

6. CONCLUSIONS

This systematic review has discussed 69 papers reporting 52 primary studies addressing RS that make use of the structured data published as Linked Data. We focused on identifying the most relevant problems that these studies aimed to solve and how they used Linked Data to provide recommendations. Although some of our results are already known, we defined a protocol to support our assumptions. Furthermore, we analyzed contributions, limitations, application domains, evaluation techniques they applied to assess their results, and the proposed directions for future research.

With regard to the research problems, we found that the most relevant ones were the lack of semantic information and the complexity of information about items. In order to overcome the lack of semantics, RS are enriched with diverse Linked Data datasets that are useful to describe users and items while reducing the ambiguity and exploiting the vast amount of links between related concepts stored in these datasets.

The majority of the selected studies have addressed these problems using Linked Data for several purposes, such as (*i*) finding new relationships or similarities based on links, paths, graphs, and created on the basis of Linked Data; (*ii*) generating serendipitous recommendations, that is, recommending items that are not expected by the users because of the links uncovered once the items are enriched with Linked Data; and (*iii*) explaining the recommendations, that is, allowing users to understand the reason of a recommendation by following the paths among items in the Linked Data cloud.

We also provided a classification of the selected studies according to the way they use Linked Data to provide recommendations. In particular, we identified four classes: Linked Data driven RS, which rely on techniques applied on datasets in Linked Data cloud such as categories, paths, number of input, and output links; hybrid RS that combine traditional techniques of recommendation (e.g., collaborative filtering and content based) with Linked Data; representation-only RS that uses Linked Data only to represent items or users but not for recommendations; and exploratory search systems that are not RS but help users to discover content through a guided search and are specially useful for users interested in learning or investigating a topic.

Additionally, we studied the most common datasets that RS use in order to obtain information, and we found that more than a half of these studies rely on DBpedia. This is because DBpedia is considered a central hub for the Linked Data cloud; it is linked to various datasets that gives the possibility to access diverse data from different application domains. Additionally, it makes DBpedia suitable for testing purposes in generic RS.

Concerning the evaluation techniques, the majority of the selected studies are focused on accuracy and rely more often on *user studies* than *comparison with other methods*. Computational complexity is also assessed in few cases; however, we think that it is an important factor to be evaluated especially for applications needing short responses such as RS in mobile environments. Additionally, we found that there is still a need for building testbeds to allow for testing and studying the results of RS based on Linked Data.

According to our findings, we identified that two recurrent issues in the selected studies are the high computational demand and the domain dependency. Therefore, we believe that further research is still needed to offer non-invasive personalization, exploit more datasets, and improve performance. Additionally, future work should focus on providing evaluation of RS considering the accuracy and computational complexity. With regard to application domains, music, movies, and tourism items are the most used in RS, and this may be due to the fact that in these domains, there are more datasets that help scientists to assess the results of their RS in comparison with similar approaches.

Finally, it is worth to mention that currently, we are working in the area of RS; in particular, we are developing RS that uses Linked Data as a source of information to recommend items for multiple application domains. The currently obtained results have been presented in [23], in which we describe how the RS based on Linked Data can be applied in the eTourism domain.

APPENDIX A. SELECTED PAPERS

Rows in italics identify papers (P) belonging to a study (S) already reported by other paper (e.g., papers 10, 19, and 54 belong to the same study S10).

Table A.1. Selected papers (P) and corresponding studies (S).

P	S	Authors	Year	Title	Publication details
1	S1	Fernández-Tobías, I., Cantador, I., Kaminskas, M., Ricci, F.	2011	A generic semantic-based framework for cross-domain recommendation	2nd International Workshop on Information Heterogeneity and Fusion in Recommender Systems - HetRec '11, pp 25 - 32
2	S2	Kabutoya, Y., Sumi, R., Iwata, T., Uchiyama, T., Uchiyama, T.	2012	A Topic Model for Recommending Movies via Linked Open Data	International Conferences on Web Intelligence and Intelligent Agent Technology, pp 625–630
3	S3	Dell'Aglio, D., Celino, I., Cerizza, D.	2010	Anatomy of a Semantic Web-enabled Knowledge-based Recommender System	4th international workshop Semantic Matchmaking and Resource Retrieval in the Semantic Web, at the 9th International Semantic Web Conference, pp 115–130
4	S4	Mannens, E., Coppens, S., Wica, I., Dacquin, H., Van De Walle, R.	2013	Automatic News Recommendations via aggregated Profiling	Journal Multimedia Tools and Applications, 63 (2), pp 407–425
5	S5	Dzikowski, J., Kaczmarek, M.	2012	Challenges in Using Linked Data within a Social Web Recommendation Application to Semantically Annotate and Discover Venues	International Cross Domain Conference and Workshop, pp 360–374
6	S6	Wardhana, A.T.A.; Nugroho, H.T.	2013	Combining FOAF and Music Ontology for Music Concerts Recommendation on Facebook Application	Conference on New Media Studies, pp 1–5
7	S7	Passant, A., Raimond, Y.	2008	Combining Social Music and Semantic Web for music-related recommender systems	First Workshop on Social Data on the Web, pp 19–30
8	S8	Lindley, A., Graf, R.	2011	Computing Recommendations for Long Term Data Accessibility basing on Open Knowledge and Linked Data	5th ACM Conference on Recommender Systems, pp 51–58

Table A.1. *Continued.*

P	S	Authors	Year	Title	Publication details
9	S9	Passant, Alexandre	2010	dbrec-Music Recommendations Using DBpedia	The Semantic Web-ISWC 2010, pp 209–224
10	S10	Stankovic, M., Breitfuss, W., Laublet, P.	2011	Discovering Relevant Topics Using DBPedia: Providing Non-obvious Recommendations	2011 International Conferences on Web Intelligence and Intelligent Agent Technology, 1, pp 219–222
11	S11	Marie, N., Gandon, F., Ribière, M., Rodio, F.	2013	Discovery Hub : on-the-fly linked data exploratory	9th International Conference on Semantic Systems, pp 17–24 search
12	S12	Peska, L., Vojtas, P.	2013	Enhancing Recommender System with Linked Open Data	10th International Conference on Flexible Query Answering Systems, pp 483–494
13	S13	Di Noia, T., Mirizzi, R., Ostuni, V. C., Romito, D.	2012	Exploiting the web of data in model-based recommender systems	6th ACM conference on Recommender systems
14	S14	Golbeck, J.	2006	Filmtrust: movie recommendations from semantic web-based social networks	3rd IEEE Consumer Communications and Networking Conference, pp 1314–1315
15	S15	Celma, Ò., Serra, X.	2008	FOAFing the music: Bridging the semantic gap in music recommendation	Web Semantics: Science, Services and Agents on the World Wide Web, 6 (4), 250–256
16	S16	Varga, B., Groza, A.	2011	Integrating DBpedia and SentiWordNet for a tourism recommender system	7th International Conference on Intelligent Computer Communication and Processing, pp 133–136
17	S17	Kaminskas, M., Fernández-Tobías, I., Ricci, F., Cantador, I.	2012	Knowledge-based music retrieval for places of interest	Proceedings of the second international ACM workshop on Music information retrieval with user-centered and multimodal strategies—MIRUM ’12, pp 19–24
18	S18	Dietze, S.	2012	Linked Data as facilitator & practice for TEL recommender systems in research	2nd Workshop on Recommender Systems for Technology Enhanced Learning, pp 7–10
19	S19	Damljanovic, D., Stankovic, M., Laublet, P.	2012	<i>Linked Data-Based Concept Recommendation : Comparison of Different Methods</i>	9th Extended Semantic Web Conference, pp 24–38
20	S19	Kitaya, K., Huang, H. H., Kawagoe, K.	2012	Music curator recommendations using linked data	Second International Conference on the Innovative Computing Technology, pp 337–339
21	S20	Jung, K., Hwang, M., Kong, H., Kim, P.	2005	RDF Triple Processing Methodology for the Recommendation System Using Personal Information	International Conference on Next Generation Web Services Practices, pp 241–246
22	S21	Calì, A., Capuzzi, S., Dimartino, M. M., Frosini, R.	2013	Recommendation of Text Tags in Social Applications Using Linked Data	ICWE 2013 Workshops
23	S21	Calì, A., Capuzzi, S., Dimartino, M. M., Frosini, R.	2013	<i>Recommendation of Text Tags Using Linked Data</i>	3rd International Workshop on Semantic Search Over the Web, pp 1–3
24	S22	Meymandpour, R., Davis, J. G.	2012	Recommendations using linked data	5th Ph.D. workshop on Information and knowledge—PIKM ’12, pp 75–82
25	S23	Harispe, S., Ranwez, S., Janaqi, S., Montmain, J.	2013	Semantic Measures Based on RDF Projections: Application to Content-Based Recommendation Systems	On the Move to Meaningful Internet Systems: OTM 2013 Conferences SE–44, pp 606–615

Table A.1. *Continued.*

P	S	Authors	Year	Title	Publication details
26	S24	Hopfgartner, F., Jose, J. M.	2010	Semantic user profiling techniques for personalised multimedia recommendation	Multimedia Systems, 16 (4-5) pp 255–274
27	S5	Lazaruk, S., Dzikowski, J., Kaczmarek, M., Abramowicz, W.	2012	<i>Semantic Web Recommendation Application</i>	Federated Conference on Computer Science and Information Systems (FedCSIS), pp 1055–1062
28	S25	Ostuni, V. C., Di Noia, T., Di Sciascio, E., Mirizzi, R.	2013	Top-N recommendations from implicit feedback leveraging linked open data	Proceedings of the 7th ACM conference on Recommender systems, pp 85–92
29	S26	Ahn, J., Amatriain, X.	2010	Towards Fully Distributed and Privacy-Preserving Recommendations via Expert Collaborative Filtering and RESTful Linked Data	International Conference on Web Intelligence and Intelligent Agent Technology, pp 66–73
30	S27	Heitmann, B., Hayes, C.	2010	Using Linked Data to Build Open, Collaborative Recommender Systems	AAAI Spring Symposium: Linked Data Meets Artificial Intelligence, pp 76–81
31	S28	Zarrinkalam, F., Kahani, M.	2012	A multi-criteria hybrid citation recommendation system based on linked data	2nd International eConference on Computer and Knowledge Engineering (ICCKE), 2012, pp 283–288
32	S29	Lommatsch, A., Kille, B., Kim, J. W., Albayrak, S.	2013	An Adaptive Hybrid Movie Recommender based on Semantic Data	10th Conference on Open Research Areas in Information Retrieval, pp 217–218
33	S30	Torres, D., Skaf-Molli, H., Molli, P.; Díaz, A.	2013	BlueFinder: Recommending Wikipedia Links Using DBpedia Properties	5th Annual ACM Web Science Conference, pp 413–422
34	S31	Ostuni, V. C., Di Noia, T., Mirizzi, R., Romito, D., Di Sciascio, E.	2012	Cinemappy : a Context-aware Mobile App for Movie Recommendations boosted by DBpedia	International Workshop on Semantic Technologies meet Recommender Systems & Big Data SeRSy 2012, pp 37–48
35	S33	Zhang, Y., Wu, H., Sorathia, V., Prasanna, V. K.	2008	Event recommendation in social networks with linked data enablement	15th International Conference on Enterprise Information Systems, pp 371–379
36	S34	Mirizzi, R., Di Noia, T.	2010	From exploratory search to web search and back	3rd workshop on Ph.D. students in information and knowledge management—PIKM '10, pp 39–46
37	S35	Khrouf, H., Troncy, R.	2013	Hybrid event recommendation using linked data and user diversity	Proceedings of the 7th ACM conference on Recommender systems, pp 185–192
38	S36	Bahls, D., Scherp, G., Tochtermann, K., Hasselbring, W.	2012	Towards a Recommender System for Statistical Research Data	2nd International Workshop on Semantic Digital Archives
39	S37	Cheng, Gong; Gong, Saisai; Qu, Yuzhong	2011	An Empirical Study of Vocabulary Relatedness and Its Application to Recommender Systems	10th International Conference on The Semantic Web – Volume Part I, pp 98–113
40	S38	Wang, Y., Stash, N., Aroyo, L., Gorgels, P., Rutledge, L., Schreiber, G.	2008	Recommendations based on semantically enriched museum collections	Web Semantics: Science, Services and Agents on the World Wide Web, 6 (4), 283–290
41	S11	Marie, N., Gandon, F., Legrand, D., Ribiére, M.	2013	<i>Discovery Hub: a discovery engine on the top of DBpedia</i>	3rd International Conference on Web Intelligence, Mining and Semantics
42	S31	Di Noia, T., Mirizzi, R., Ostuni, V. C., Romito, D., Zanker, M.	2012	Linked open data to support content-based recommender systems	8th International Conference on Semantic Systems

Table A.1. *Continued.*

P	S	Authors	Year	Title	Publication details
43	S31	Ostuni, Vito Claudio; Gentile, Giosia; Noia, Tommaso Di; Mirizzi, Roberto; Romito, Davide; Sciascio, Eugenio Di	2013	Mobile Movie Recommendations with Linked Data	International Cross-Domain Conference, pp 400–415
44	S31	Mirizzi, R., Di Noia, T., Ragone, A., Ostuni, V. C., Di Sciascio, E.	2012	Movie recommendation with DBpedia	3rd Italian Information Retrieval Workshop, pp 101–112
45	S39	Waitelonis, J., Sack, H.	2011	Towards exploratory video search using linked data	Multimedia Tools and Applications, 59 (2), pp 645–672
46	S40	Li, S., Zhang, Y., Sun, H.	2010	Mashup FOAF for Video Recommendation LightWeight Prototype	7th Web Information Systems and Applications Conference, pp 190–193
47	S41	Hu, Y., Wang, Z., Wu, W., Guo, J., Zhang, M.	2010	Recommendation for Movies and Stars Using YAGO and IMDB	12th International Asia-Pacific Web Conference, pp 123–129
48	S42	Ruotsalo, T., Haav, K., Stoyanov, A., Roche, S., Fani, E., Deliae, R., Mäkelä, E., Kauppinen, T., Hyvönen, E.	2013	SMARTMUSEUM: A mobile recommender system for the Web of Data	Web Semantics: Science, Services and Agents on the World Wide Web, 20, pp 50–67
49	S43	Stankovic, M., Jovanovic, J., Laublet, P.	2011	Linked Data Metrics for Flexible Expert Search on the Open Web	8th Extended Semantic Web Conference, pp 108–123
50	S44	Ozdikis, O., Orhan, F., Danismaz, F.	2011	Ontology-based recommendation for points of interest retrieved from multiple data sources	International Workshop on Semantic Web Information Management, pp 1–6
51	S45	Debattista, J., Scerri, S., Rivera, I., Handschuh, S.	2012	Ontology-based rules for recommender systems	International Workshop on Semantic Technologies meet Recommender Systems & Big Data, pp 49–60
52	S46	Codina, V.; Ceccaroni, L.	2010	Taking Advantage of Semantics in Recommendation Systems	2010 Conference on Artificial Intelligence Research and Development, pp 163–172
53	S9	Passant, A., Decker, S.	2010	Hey! Ho! Let's Go! Explanatory Music Recommendations with dbrec	7th Extended Semantic Web Conference, pp 411–415
54	S10	Stankovic, M., Breitfuss, W., Laublet, P.	2011	Linked-data based suggestion of relevant topics	7th International Conference on Semantic Systems, pp 49–55
55	S9	Passant, A.	2010	Measuring semantic distance on linking data and using it for resources recommendations	AAAI Spring Symposium: Linked Data Meets Artificial Intelligence, pp 93–98
56	S14	Golbeck, J.	2006	Generating Predictive Movie Recommendations from Trust in Social Network	4th International Conference, iTrust 2006, pp 93–104
57	S39	Sack, H.	2009	Augmenting Video Search with Linked Open Data	International Conference on Semantic Systems, pp 550–558
58	S47	Baumann, S., Schirru, R., Streit, B.	2011	Towards a Storytelling Approach for Novel Artist Recommendations	8th International Workshop, AMR 2010, Linz, Austria, August 17–18, 2010, Revised Selected Papers, pp 1–15
59	S48	Corallo, A., Lorenzo, G., Solazzo, G.	2006	A Semantic Recommender Engine Enabling an eTourism Scenario	10th International Conference, pp 1092–1101

Table A.1. *Continued.*

P	S	Authors	Year	Title	Publication details
60	S49	Nuzzolese, A. G., Presutti, V., Gangemi, A., Musetti, A., Ciancarini, P.	2013	Aemoo: Exploring Knowledge on the Web	Proceedings of the 5th Annual ACM Web Science Conference, pp 272–275
61	S49	Musetti, A., Nuzzolese, A., Draicchio, F., Presutti, V., Blomqvist, E., Gangemi, A., Ciancarini, P.	2012	<i>Aemoo: Exploratory Search based on Knowledge Patterns over the Semantic Web</i>	<i>Semantic Web Challenge</i>
62	S47	Baumann, S., Schirru, R.	2012	<i>Using Linked Open Data for Novel Artist Recommendations</i>	<i>13th Internal Society for Music Information Retrieval Conference</i>
63	S50	Cantador, I., Castells, P.	2006	Multilayered Semantic Social Network Modeling by Ontology-Based User Profiles Clustering: Application to Collaborative Filtering	Proceedings of 15th International Conference, pp 334–349
64	S34	Mirizzi, R., Ragone, A., Di Noia, T., Di Sciascio, E.	2010	<i>Ranking the Linked Data: The Case of DBpedia</i>	<i>10th International Conference</i> , pp 337–354
65	S51	Heitmann, B., Hayes, C.	2010	Enabling Case-Based Reasoning on the Web of Data	The WebCBR Workshop on Reasoning from Experiences on the Web at International Conference on Case-Based Reasoning
66	S52	Alvaro, G., Ruiz, C., Córdoba, C., Carbone, F., Castagnone, M., Gómez-Pérez, J. M., Contreras, J.,	2011	miKrow : Semantic Intra-enterprise Micro-Knowledge Management System	8th Extended Semantic Web Conference, pp 154–168
67	S50	Cantador, I., Castells, P., Bellogín, A.	2011	<i>An Enhanced Semantic Layer for Hybrid Recommender Systems: Application to News Recommendation</i>	<i>Int. J. Semant. Web Inf. Syst.</i> , 7 (1), pp 44–78
68	S32	Cantador, I., Konstas, I., Jose, J. M.	2011	Categorising social tags to improve folksonomy-based recommendations	Web Semantics: Science, Services and Agents on the World Wide Web, 9 (1), pp 1–15
69	S29	Lommatsch, A., Kille, B., Albayrak, S.	2013	<i>A Framework for Learning and Analyzing Hybrid Recommenders based on Heterogeneous Semantic Data Categories and Subject Descriptors</i>	<i>10th Conference on Open Research Areas in Information Retrieval</i> , pp 137–140

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An Overview: Metacognition in Education

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Abstract

Metacognition refers to “thinking about thinking” or our ability to know what we know, what we don’t know and how to regulate as well as control such thinking. This article seeks to give an overview of some issues related to metacognition, a construct which received a considerable attention on the part of teaching theoreticians and researchers. It starts with a brief introduction of metacognition and then gives an account of its various definitions and components. The differences between cognition and metacognition are also mentioned. It concludes with some ideas and research findings on the teachability of this construct in different fields of study, especially language education.

Keywords: Metacognition, Metacognitive knowledge, Metacognitive regulation, Self-regulation, Learner autonomy

1. Introduction

It is by no means easy to talk about metacognition, an apparently unproblematic thirteen-letter term, and its education, both due to the richness and heterogeneity of theoretical and methodological approaches and due to the vague and slippery nature of the metacognition construct. “Hardly does anyone question the reality or the importance of metacognition” (Schraw & Moshman, 1995, p. 351). Tobias et al. (1999 & 2009) argued that metacognition very probably is the most dynamically and actively researched cognitive process in areas of current developmental, instructional, and educational psychology. To put it simply, metacognition refers to “thinking about thinking” or our ability to know what we know and what we don’t know (Costa & Kallick, 2009; Livingston, 1997). In actuality, offering a definition of metacognition is much more complex than that and is not that simple. There are considerable debates over what exactly this umbrella term is. It has been considered as a fuzzy concept of multifarious definitions by many researchers (Flavell, 1981).

Beyond dispute, the seeds for research programs and development in metacognition were planted and begun to germinate by John Flavell, the pioneer of the field, who deserves great credit for highlighting the depth of his knowledge on metacognition in his landmark pioneering publications on the subject. Metacognition was characterized by Flavell as a “promising new area of investigation” (1979, p. 906). Thereafter, a multitude of empirical and theoretical researches have pursued an agenda on which metacognition was high. Although the term ‘metacognition’ has not been part of educational

psychologists’ lexicon and did not come into common use until the 1970s when it was introduced by the aforementioned psychologist. The concept has been around for as long as humans have been able to reflect on their own thinking.

Legitimate grounds exist to heartily endorse a large body of research undertaken on the subject in order to bring unchallenged supremacy of metacognition and give momentum to it as one of the bare essentials to successful learning. To start with, metacognition nurtures independent thinkers and lifelong learners who are able to grapple with new situations and learn how to learn and continue to learn throughout their lifespan in this hectic pace of life (Eggen & Kaucak, 1995; El-Koumy, 2004; Papaleontiou-Louca, 2003 & 2008; Pilling-Cormick & Garrison, 2007). In the second place, incorporation of metacognition into language teaching can instill a sense of duty and confidence into learners which enables them to self-direct their own learning (Garb, 2000). A necessary step is metacognitive awareness in moving towards learning to regulate learning (Williams & Burden, 1997). The last reason is that metacognition was validated to be central to effective language learning. It is worth emphasizing the point that there is continuing evidence that well-developed metacognitive strategies are the distinguishing quality between good and poor language learners (O’Malley et al., 1989; Gillette, 1990; Rubin, 2005). In the similar vein, Macaro (2001) adds:

Although it is the range and combinations of all strategies that ineffective learners lack, it is the metacognitive ... strategies which seem to be the strategy types most lacking in the arsenal of less successful learners.” (p. 269) Needless to say, sitting there cross-

legged and comfortably waiting hopefully and expecting confidently for learners to automatically “go meta” and self-regulate their own learning seems quite impossible and unrealistic. In a metaphorical sense, “Going meta” connotes becoming an audience for your own performance, that is to say, stepping back to see what you are doing, as though you were someone else actually witnessing it. Learning how to be mindful and manager of one’s own learning is not inherited, nor does it happen naturally and overnight, yet it necessitates specific instruction of basic metacognitive skills and strategies. The good news is that metacognitive skills are teachable and learnable as well to build up support for learners to better regulate their cognitive activities (Livingston, 1997; Shannon, 2008; Baer et al., 1994; Brown et al., 1983; Flavell, 1979a; Garner & Alexander, 1989; Borkowski et al., 1987; Bransford et al., 1986; Garner, 1990; Hascher & Oser, 1995). Needed is a big challenge in the howness of instilling and developing metacognition into students in order for helping students learn how to “go meta” concerning mental processes that are not visible directly to create virtuoso performance as learners in their learning experience. Sternberg (2009) contends that:

In the early days, metacognition was more of a curiosity and some psychologists wondered whether it was even a viable construct. Today, I think the question is not whether it is a viable construct, but rather, how it best can be understood, assessed, and developed [taught]. (P. ix)

Metacognition currently carves a unique and successful niche in the self-regulatory phylum and its instruction is a highly flexible and an indispensable approach to language education in that more proficient language learners are more metacognitive than less proficient language learners.

2. Origins and Development

Unquestionably, John Flavell, a developmental psychologist who is now considered to be as the father of the field, was the first one who introduced the term *metacognition* in the 1970s (1971, 1976, 1979). It is defined as “a critical analysis of thought,” or simply “thinking about thinking” or “cognition about cognition” (Wellman, 1985; Anderson, 2008; Livingston, 1997). Metacognition can concentrate on any facet of cognition, even metacognition itself (Dunlosky, et al, 2005; Nelson & Narens, 1994). Veenman et al. (2006) regard metacognition as “... a higher-order agent overlooking and governing the cognitive system, while simultaneously being part of it” (p. 5). In his model of cognitive monitoring, Flavell himself offers an early definition of ‘metacognition’ as:

One’s knowledge concerning one’s own cognitive processes and products or anything related to them (...) [and] refers, among other things, to the active monitoring and consequent regulation and orchestration of these

processes (...), usually in the service of some concrete goal or objective. (Flavell, 1976, p. 232)

What is clear from Flavell’s above account, the main constituents of metacognition are “*metacognitive knowledge* and *metacognitive experience or regulation*”. In addition, he established a link between metacognition and self-regulated learning by making use of the phrase “cognitive monitoring” (Griffith & Ruan, 2005, p. 3). According to Burke (2007), metacognitive skills are sometimes called “self-direction skills” (p. 151).

Based on the proposed model of cognitive monitoring, Flavell held a belief that a wide range of intellectual activities will be monitored by means of the actions and interactions among four basic elements: a) metacognitive knowledge, b) metacognitive experience, c) goals (or tasks), and d) actions (or strategies). *Metacognitive knowledge* refers to one’s knowledge or beliefs about person, task, and strategy variables. He has affirmed that metacognitive knowledge is not basically different from other kinds of knowledge in the long-term memory. *Metacognitive experiences* are the segments of this stored knowledge, metacognitive knowledge, that have entered to consciousness, that is, “any conscious cognitive or affective experiences that accompany and pertain to any intellectual enterprise” (Flavell, 1979, p. 906). Metacognitive experiences are very likely to take place in circumstances which requires a great deal of careful, highly ‘conscious thinking’. Metacognitive knowledge can be added, deleted, or revised through metacognitive experiences. The *goals or tasks* have to do with the actual objectives of a cognitive endeavor. And finally *actions or strategies*, as the name indicates, are some ways and techniques that may assist in reaching those goals. According to Flavell (1979), acquiring metacognitive strategies as well as cognitive ones is viable. To illustrate the point, Flavell makes some helpful cases of metacognition in real-life experiences

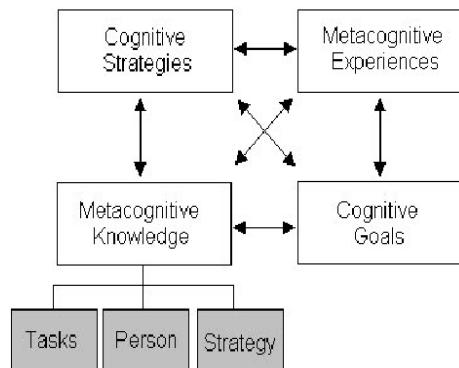


Figure 1: Flavell’s model of metacognition (1981, p. 40)

I am engaging in metacognition if I notice that I am having more trouble learning A than B; if it strikes me that I should double-check C before accepting it as a fact; (...) if I become aware that I am not sure what the experimenter really wants me to do; if I sense I had better make a note

of D because I may forget it; if I think to ask someone about E to see if I have it right. (Flavell, 1976, p. 232)

Most researchers have now conceptualized metacognition as including two fundamental elements or components referred to as *knowledge of cognition* and *regulation of cognition* (Jacobs & Paris, 1987; Schraw & Moshman, 1995; Schraw, 1998; Brown, 1987; McCormick, 2003; Harris et al., 2010; Williams & Atkins, 2009). Knowledge of cognition refers to knowledge and awareness of one's own cognition. Metacognitive knowledge is "potentially conscious and controllable" (Pressley et al., 1985, p. 4). Moreover, knowledge of cognition or metacognitive knowledge can be stable, usually statable, often fallible, and often late developing information which human as an independent thinker has about his own cognitive process (Baker & Brown, 1984; Garner, 1987; Brown, 1987).

Metacognitive knowledge has been presumably comprised of three distinct, but closely related, facets of knowledge: *declarative*, *procedural*, and *conditional* knowledge (McCormick, 2003; Paris et al., 1983; Harris et al., 2010). Successful coordination and application of these three types of metacognitive knowledge will surely leave its mark on academic development and performance which is heavily contingent upon metacognition (Alexander, 1997; Pressley & Harris, 2006).

Declarative knowledge involves knowledge, skills, and strategies essential for accomplishing a task successfully under various conditions (Hacker, 1998; Pressley & Harris, 2006; Zimmerman & Risemberg, 1997). In other words, it refers to knowing "about things" or "knowing what". Schraw and Moshman (1995) define it as "knowledge about oneself as a learner and about what factors influence one's performance" (p. 352). Flavell (1979) discriminated between kinds of declarative knowledge along the aspects of self or person, task, and strategies or actions.

Procedural knowledge refers to knowledge of how to apply procedures such as learning strategies or actions to make use of declarative knowledge and achieve goals (Harris et al, 2009; Harris et al, 2010; Schraw & Moshman, 1995; Schraw, 1998; McCormick, 2003). It pertains to knowing "how to do things" and "procedures" such as learning strategies. Skilled learners possess more automatic, accurate, and effective procedural knowledge than unskilled learners.

Finally, *conditional knowledge* is referred to as knowledge of when and why to apply various procedures, skills, and cognitive actions or strategies (McCormick, 2003; Schraw & Moshman, 1995; Schraw, 1998; Garner, 1990). Harris et al. (2010) define it as "knowing when, where, and why to use declarative knowledge as well as particular procedures or strategies (procedural knowledge), and is critical to effective use of strategies" (Harris et al., 2009, p.133). In the same way, Garner (1990) held that conditional knowledge is related to knowing when and why to use declarative and procedural

knowledge. It is appropriate to add that "[t]he conditional knowledge of successful learners makes them very facile and flexible in their strategy use" (McCormick, 2003, P. 80).

Regulation of cognition or metacognitive control is the second major element of metacognition, sometimes also is referred to as executive control, is a sequence of actions taken by students to control their own thinking or learning. It encompasses at least three basic components or essential skills of *planning, monitoring, and evaluation* (Jacobs & Paris, 1987; Schraw & Moshman, 1995; Schraw, 1998).

Planning includes the selection of proper strategies and the provision of resources effective for reaching goals, for instance, making predictions before reading. It includes goal setting, activating prior knowledge, and budgeting time.

Monitoring includes the self-testing skills essential to regulate learning. It refers to the critical analysis of the effectiveness of the strategies or plans being implemented. Schraw (1998) has treated it as "one's online awareness of comprehension and task performance" (p.115). Engaging in periodic self-testing in the course of learning would be a particular case of monitoring.

Evaluation refers to the examination of progress being made toward goals which can trigger further planning, monitoring, and evaluation. A typical example might be re-evaluating one's goals and conclusions. To put a fitting end to the discussion on components of metacognition two crucial points are required to be taken into consideration with regard to metacognitive knowledge and metacognitive regulation. Firstly, metacognitive knowledge and experience are related to each other and form partially overlapping sets. Furthermore, they complement and enrich each other. Next, metacognitive knowledge and metacognitive regulation are domain-general in nature and both components appear to embrace a wide spectrum of subject areas and domains.

Gradually, the concept of metacognition underwent some changes and modifications to embrace anything psychological, rather than just anything cognitive (Papaleontiou-Louca, 2003 & 2008). Albeit, when making the first genuine attempt to clearly define the construct of metacognition, Flavell (1979) personally makes reference to the concept as to all those conscious *cognitive* and *affective* experiences that associated with a cognitive enterprise. Flavell (1987) expands the concept of metacognition in a more explicit way to include not only cognitive variables, but rather, anything affective.

In fact, the current literature available on metacognition brings the term to completion by including not only 'thoughts about thoughts', its former definition, but also the following notions: knowledge of one's knowledge, processes, and cognitive and affective states, and the ability to consciously and deliberately monitor and regulate one's knowledge, processes, and cognitive and affective states (Papaleontiou-Louca, 2008).

An important issue which warrants consideration and mention is that the application of knowledge of one's own cognitive and affective processes and the regulation of these processes do not take place in a vacuum, yet, as many theorists and models of metacognition suggest, are highly influenced by one's goals, motivations, perceptions of ability, attributions, and beliefs, as well as context, such as social and cultural norms (Borkowski, et al., 1992; Paris & Winograd, 1990a; Schunk, 1989). Obtaining a full better understanding of metacognition is contingent upon taking these major factors into due consideration as they constitute influences on metacognition as well as being influenced by metacognition (see Borkowski et al., 2000; Pintrich & Zusho, 2002; Zimmerman, 2002).

3. Metacognition versus Cognition

One noteworthy discrimination for fathoming out the true character of the concept of metacognition is to elucidate the distinction between metacognition and cognition (Nelson, 1999; Nelson & Narens, 1994). Nelson (1999) refers to metacognition as "the scientific study of an individual's cognitions about his or her own cognitions" (p. 625). Therefore, metacognition can be considered as a subset of cognition, better to say, a certain kind of cognition. Broadly defined, cognition is a general term for thinking, while metacognition is thinking about thinking.

According to Flavell (1979), metacognition and cognition differ in terms of their content and function, not in their form and quality, i.e., both can be acquired and forgotten, be either correct or incorrect, and so forth. It is safe to say that the aforementioned idea seems an ideal point of departure to draw a sharp distinction between metacognition and cognition. From such a view, the *contents* of metacognition are the knowledge, skills, strategies, and information about cognition, a portion of mental world, while cognition has to do with things in both external and mental world (Amado Gama, 2005). Hacker (1998) articulates that

Metacognitive thoughts do not spring from a person's immediate external reality; rather, their source is tied to the person's own internal mental representations of that reality, which can include what one knows about that internal representation, how it works, and how one feels about it. (Hacker, 1998, p. 3)

From *function* side, cognition acts to resolve problems and bring cognitive activity to a desirable outcome, while metacognitive function is the monitoring and regulation of an individual's cognitive effort in solving a problem and executing a task (Vos, 2001). Cognitive strategies are those strategies which assist a person in accomplishing a particular goal (e.g., comprehending a text), while metacognitive strategies refer to control or regulatory processes such as planning, monitoring, and evaluation, which individuals use to ensure that the particular goal has been met (Livingston, 1997; Rubin, 2005; Garner;

1987). That is to say, "cognitive skills facilitate task achievement, and metacognitive skills help to regulate task achievement" (McCormick, 2003, p. 81).

4. Metacognition, Instruction and Learning

"In teaching me independence of thought, they had given me the greatest gift an adult can give to a child besides love, and they had given me that also." (Courtenay, 1989, p. 326, cited from Paris & Winograd, 1990a, p. 7)

Although much remains to be learned about metacognition, a topic with an honorable history in psychology and education, without question, the fundamental question "Can metacognition or metacognitive strategies be taught or developed?" which has exercised the minds of researchers for quite a long time is no longer an unanswered question drawing on the strong legacy of the research on the topic, but rather a legitimate question with a satisfactory and definite answer, an *emphatic 'yes'* (Bandura, 1986; Hofer & Yu, 2003; Sperling et al., 2004; Borkowski et al., 1987; Bransford et al., 1986; Garner, 1990; Cromley, 2000; Kuhn et al., 1997; Daley, 2002; Schunk, 1990; Israel, 2007). In instilling metacognitive strategies into students, however, one needs to be cautious and aware that metacognition develops slowly and is difficult to teach (Vos, 2001).

Following the coinage of the term 'metacognition', Flavell (1979) claimed that "increasing the quantity and quality of children's metacognitive knowledge and monitoring skills through systematic training may be feasible as well as desirable" (p. 910). Furthermore, Flavell takes a broad vision regarding metacognitive development and offers a beacon of hope that:

It is at least conceivable that the ideas currently brewing in this area could someday be parlayed into a method of teaching children (and adults) to make wise and thoughtful life decisions as well as to comprehend and learn better in formal educational setting. (Flavell 1979, p. 910)

With regard to the centrality of metacognition to learning, Flavell (1979) contends, though with little empirical evidence, that metacognition plays an important role in varying areas of learning such as oral communication of information, oral persuasion, oral comprehension, reading comprehension, writing, language acquisition, attention, memory, problem solving, social cognition, and various types of self-control and self-instruction (p. 906). According to Sternberg (2009), viability and attainment of metacognition is beyond question, yet the question is how it best can be conceptualized, evaluated, and enhanced. Likewise, Kuhn (2000) asserts that what is perhaps the most significant question which necessitates more investigation is "How can metacognitive development be facilitated?" (p. 180).

The potentiality of increasing meaningfulness of students' learning in various fields has been

demonstrated by an enormous body of research (e.g. Biggs, 1986; Hartman, 2001a; Pressley & Ghatala, 1990; Paris & Winograd, 1990b; Brown & Palinscar, 1982). Metacognition "has the potential to empower students to take charge of their own learning and to increase the meaningfulness of students' learning" (Amado Gama, 2005, p. 21), it also encourages learners to 'learn what to do when they don't know what to do' (Wade, 1990; Claxton, 2002). Similarly, Chamot et al. (1999) stated that "metacognition or reflecting on one's own thinking and learning is the hallmark of the successful learner" (p. 2). With regard to metacognitive strategies, with the wisdom of a multitude of research, it is safe to say that the more metacognitive one is, the more strategic and successful one is to be in learning; to be more exact, an individual can pull himself up by his bootstraps in his own lifelong learning (Borkowski et al., 1987; Garner & Alexander, 1989; Pressley & Ghatala, 1990; Schraw & Dennison, 1994). On the value of metacognition, Kuhn (2000) rightly puts that

There would seem few more important accomplishments than people become aware of and reflective about their own thinking and able to monitor and manage the ways in which it is influenced by external sources, in both academic, work, and personal life setting. Metacognitive development is a construct that helps to frame this goal. (p. 181)

Concerning to the instruction and development of metacognition, Papaleontiou-Louca (2003) asserts that "[m]etacognition, like everything else, undoubtedly develops with practice" (p. 17). It is believed that metacognition includes *strategies* for planning, monitoring, and evaluating of language use and language learning which are considered as key elements in developing autonomy (Harris, 2003). If education aimed at helping learners to take charge of their own learning, they have to be able to plan, monitor, and evaluate their learning processes. To do so, they need to be metacognitively aware (Hacker et al., 2009). Ariel (1992) suggests that the aim of metacognitive instruction is to ... develop the sensitivity of students to learning situations, to heighten students' awareness of their own cognitive repertoire and the factors that affect the learning process and contribute to successful learning, to teach strategies for learning, and to develop students' capacity to regulate and monitor their activities. (p. 82).

Just like giving a sick person a useless placebo injection, simply providing learners with answers may enable them to resolve the immediate learning problem. Though, it is not a panacea, just a partial remedy that causes definitely as many problems as it solves. Yet, extolling the virtues of metacognition, many researchers take the view that it has the potential to be seen as a kind of panacea for most learning problems learners may encounter through germination of strategies empowering them to manage their own learning and find out the answers by themselves. "Metacognition can provide

students with knowledge and confidence that enables them to manage their own learning and empowers them to be inquisitive and persistent in their pursuits" (Paris & Winograd, 1990a, p. 11).

As pertains to metacognitive development, simply providing learners with highly regimented and structured instruction in metacognitive knowledge without metacognitive experience or quite reverse seems to be insufficient for and does not guarantee the development of metacognitive control and self-regulation (Livingston, 1996 & 1997). Thereby, in fostering a culture of metacognition in learners and classroom settings, the most efficacious approach, though there are several approaches, is the one into which both components of metacognition, namely metacognitive knowledge, and metacognitive regulation are incorporated. One which provides the learners with both knowledge of cognitive processes as well as strategies and together with experience or practice in deploying both cognitive and metacognitive strategies and self-evaluation of the outcomes of their learning.

Anderson (2008) suggested that metacognition in language learning can be divided into five primary and intersecting components: 1. Preparing and planning for learning, 2. Selecting and using strategies, 3. Monitoring learning, 4. Orchestrating strategies, and 5. Evaluating learning. It merits a mention that each of these five components of metacognition is engaged in an interactive process which is not of a linear nature, moving from preparation and planning to evaluation, rather a cyclic one.

McCormick (2003) articulated that "[s]ince it has become clear that metacognitive awareness and skills are a central part of many academic tasks, a critical question for educators is how we foster the development of metacognition in students" (p. 90). Incontrovertibly, a great deal more research is required before one can answer this question with any authority. As a grand finale and conclusion to the discussion in this part, a verbatim quote of Anderson (2008) is worth mentioning.

While learning from a good teacher in a well-structured language program is very important, it is perhaps even more important for these learners to have meaningful learning experiences on their own. Good teachers and well-structured language learning programs cannot possibly teach learners everything they need to know. Getting good results from a study depends on learners' going beyond what teachers and programs provide and developing the kind of metacognitive behavior which will enable them to *regulate their own learning*. (Emphasis added, p. 108)

5. Conclusion

This paper made an attempt to provide a brief overview of metacognition by examining its background and summarizing the relevant literature. It has also outlined

some basic features and different components of Metacognition. A summary of research findings on metacognitive strategy training in some areas of education have also been included. Metacognition is a powerful construct in today's educational setting, and its principled teaching can instill a sense of independence and autonomy into learners.

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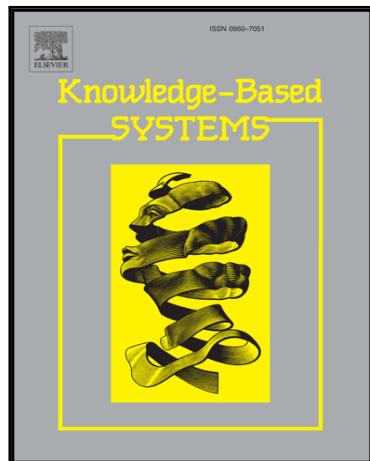
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Characterizing Context-Aware Recommender Systems: A Systematic Literature Review

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Abstract

Context-aware recommender systems leverage the value of recommendations by exploiting context information that affects user preferences and situations, with the goal of recommending items that are really relevant to changing user needs. Despite the importance of context-awareness in the recommender systems realm, researchers and practitioners lack guides that help them understand the state of the art and how to exploit context information to smarten up recommender systems. This paper presents the results of a comprehensive systematic literature review we conducted to survey context-aware recommenders and their mechanisms to exploit context information. The main contribution of this paper is a framework that characterizes context-aware recommendation processes in terms of: i) the recommendation techniques used at every stage of the process, ii) the techniques used to incorporate context, and iii) the stages of the process where context is integrated into the system. This systematic literature review provides a clear understanding about the integration of context into recommender systems, including context types more frequently used in the different application domains and validation mechanisms—explained in terms of the used datasets, properties, metrics, and evaluation protocols. The paper concludes with a set of research opportunities in this field.

Keywords: Recommender systems, Context-aware recommender systems, Pre-filtering, Post-filtering, Context modeling, Recommender systems evaluation

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1. Introduction

With the proliferation of big data & data analytics technologies, recommender systems (RS) are now crucial in seeking customer satisfaction through personalization [1]. RS aim at selecting and proposing the most relevant items, services and offers for their users, by considering their profiles, purchase history, preferences, opinions, interactions with offered products and services, as well as their relationships with other clients. At the same time, the generalization of smart-phones and ubiquitous computing has given RS access to context information [2]. Context-aware recommender systems (CARS) go one step further from traditional RS by exploiting context information such as time, location, and user activity to understand user situations and their influence on user preferences. The incorporation of context information into RS [2, 3] leverages the value of these systems by improving the relevance of possible recommendations with respect to changing user needs [4, 5].

The value of context information to improve the quality of recommendations has been demonstrated and supported by different researchers [6, 7, 8, 9, 10, 11]. Nevertheless, RS as well as context-awareness researchers and practitioners interested in combining the two areas still lack a guide that helps them understand how to exploit context information to smarten up RS. Evidence of this is the absence of comprehensive and domain-independent surveys, particularly systematic literature reviews, that not only consolidate the state of the art of the field, but also explain the most common techniques used to integrate context into the recommendation process. After a rigorous revision of the state of the art, we found that none of the available surveys comprehensively characterize recommendation processes from the perspective of the exploitation of context information. In the best cases, existing surveys focus only on the identification of used context types, and most of them address the problem from the perspective of a particular domain.

This paper presents the findings of a systematic literature review (SLR) [12] on CARS that we conducted with the goal of helping practitioners and researchers understand how context information can be effectively combined with recommendation mechanisms. To this end, we studied a final set of 87 CARS papers that were classified as content-based, collaborative filtering and hybrid approaches. For each paper, we identified recommendation

techniques, means to exploit context information, context types, application domains, validation mechanisms including the used datasets, the improvements obtained through the exploitation of context (when measured quantitatively), and research opportunities. The main results of our study are reported in this paper in the form of a framework that characterizes recommendation processes in terms of: i) the recommendation techniques used at every stage of the process, ii) the techniques used to incorporate context, and iii) the stages of the process where context is integrated into the system. This manuscript aims at providing a clear understanding about where context information is usually integrated into the system, what techniques are available to exploit context information depending on the underlying recommendation approach and the phase of the process where context is included, what context types are more frequently exploited in the different application domains, and what validation mechanisms—explained in terms of the used datasets, properties, metrics and evaluation protocols—are generally used to evaluate the proposed approaches. Last, but not least, the paper discusses research opportunities relevant to CARS.

This paper is structured as follows. Sect. 2 explains foundational concepts on recommender systems and context information. Sect. 3 visits related work by analysing the contributions of our SLR with respect to other surveys published on CARS. Sect. 4 explains the methodology we followed to conduct the SLR. Sects. 5–8 constitute the contributions of this manuscript: Sect. 5 presents the findings of our SLR and the characterization framework for CARS; Sect. 6 reports on the validation methods and datasets identified in the studied approaches; Sect. 7 presents quantitative data, reported in the studied papers, on the improvements obtained from the exploitation of context information; and Sect. 8 summarizes and classifies research opportunities. Finally, Sect. 9 concludes the paper.

2. Background

This section briefly presents the fundamentals of RS, and context information as an enabler to improve the quality of recommendations.

2.1. Recommender systems (RS)

Dating back to the mid 1990s, the first recommender systems emerged by following two well differentiated paths. On the one hand, *content-based recommenders* drew from the fields of document retrieval [13, 14] and user

profiling [15] to define a common representation space for describing items and users. User profiles result from the aggregation of items that have been favorably or unfavorably qualified in the past. For a given user, items similar to the user's profile are recommended, without taking into account information from other users. On the other hand, *collaborative filtering recommenders* evolved from contributions in human computer interaction [16, 17], where the preferences and choices of similar users are used as the basis for recommendation.

Each of these two types of systems has advantages and disadvantages. Content-based recommenders are easy to explain and understand, prove a good starting point for item navigation, and allow recommendations for new users and/or items (cold start problem). However, they imply the cumbersome task of thoroughly and explicitly describing all items using a common set of features, do not work with implied content, can only handle complementary item recommendation and, being centered on a single user, do not allow the recommendation of serendipitous items. In contrast, collaborative filtering recommenders are based on the common preferences of crowds of users. Thus, these systems cannot only recommend complementary as well as substitute items, but also surprise users by recommending unusual items. Nevertheless, they are not as transparent on their recommendations, need substantially more user data to work well, and do not provide a way to deal with the cold start problem.

Hybrid recommenders, a third type of RS, provide a middle ground between content-based and collaborative filtering systems, by leveraging their strengths and mitigating their drawbacks.

This categorization of RS was proposed by Adomavicius and Tuzhilin in [6]. Other authors have proposed other types of systems [1, 18]. In particular, we consider case-based and knowledge-based systems to be subtypes of the content-based family, community-based systems to be subtypes of the collaborative filtering family, and demographic recommenders to be either content-based or collaborative filtering systems following a pre-filtering stage where data are partitioned in subsets according to user characteristics.

RS use information from items, users, and preferences. The main source of information is the item by user matrix that stores user preferences for individual items. These preferences can be explicitly stated (e.g., in the form of ratings or likes), or implicitly inferred from the interactions of the user with the system (e.g., purchases, accesses or reads). Content-based recommenders consider additional sources of information in the form of feature vectors de-

scribing different characteristics of each item (e.g., category, size, age, brand, author).

The characterization of CARS presented in this paper is driven by the stages of the processes followed by content-based and collaborative filtering systems.

2.2. Context information

Abowd et al. define *context* as “*any information useful to characterize the situation of an entity (e.g., a user or an item) that can affect the way users interact with systems*”[2]. The precision of recommendations may result highly affected by context information [7, 8]. For example, a costumer could be more or less interested in a particular restaurant depending on the day of the week. Contextual information can be defined as static or dynamic [3]. When context is static, recommender applications assume that this information is immutable over time. An example of static context is the birthday of a user. On the contrary, dynamic context changes over time thus highly affecting user current needs. Instances of dynamic context are location, time, and user activity [5].

2.2.1. Context categories

Villegas et al. [5] characterize context along five general categories: individual, location, time, activity, and relational. Other characterizations, which can be instantiated from these general categories, have been proposed for domain specific CARS (e.g., the one proposed by Verbert et al. in [19] for CARS in the learning realm). To identify the context types exploited by the CARS studied in this SLR, we based on the classification of context information proposed by Villegas et al., which is summarized as follows:

- **Individual context:** Corresponds to information observed from independent entities (e.g., users or items) that may share common features. This category can be sub-classified into *natural*, *human*, *artificial*, or *groups of entities*. *Natural context* represents characteristics of living and non-living entities that occur naturally, that is, without human intervention (e.g. weather information). *Human context* describes user behavior and preferences (e.g., user payment preferences). *Artificial context* describes entities that result from human actions or technical processes (e.g., hardware and software configurations used in e-commerce platforms). The last subcategory, *groups of entities*, concerns groups of independent subjects that

share common features, and that might relate each other (e.g., preferences of users in the user's social network).

- **Location context:** Refers to the place associated with an entity's activity (e.g., the city where a user lives). This category is sub-classified as *physical* (e.g., the coordinates of the user's location, a movie theater's address, or the directions to reach the movie theater from the costumer's current location), and *virtual* (e.g., the IP address of a computer that is located within a network).
- **Time context:** Corresponds to information such as time of the day, current time, day of the week, and season of the year. Time context can be categorized as *definite* and *indefinite*. *Definite* context indicates time frames with specific begin and end points. *Indefinite* context refers to recurrent events that occur while another situation takes place, so it does not have a defined duration (e.g. a user's session in an e-commerce application).
- **Activity context:** Refers to the tasks performed by entities (e.g., shopping, the task a user does at a particular time).
- **Relational context:** Refers to entity relationships that arise from the circumstances in which the entities are involved [20]. Relational context can be defined as *social* (i.e., interpersonal relations such as associations or affiliations), *functional* (i.e. the usage than an entity makes of another).

2.2.2. Integrating Context into Recommender Systems

Traditional recommender systems rely on information about users and items. In contrast, CARS rely also on context information that is relevant for the recommendation. Therefore, recommendation tasks in context-aware recommender systems can be seen as a function of users, items and context information [8]:

$$f : \text{Users} \times \text{Items} \times \text{Context} \rightarrow R \quad (1)$$

There exists three paradigms to integrate context information into recommender systems, depending on the phase of the recommendation process at which context is processed [8]:

- **Contextual pre-filtering:** Context information is used as a filtering mechanism applied to the data, before the application of the recommendation model.

- **Contextual post-filtering:** Context information is initially ignored, and preferences are computed by applying traditional recommender algorithms on the entire data. The resulting set of recommendations is then filtered according to context information that is relevant to the user.
- **Contextual modeling:** Context information is directly integrated into the recommendation model, for example as part of the preference computation process.

This SLR characterizes CARS by considering these three paradigms to incorporate context into the recommendation process, and the techniques used for this integration.

3. Related work

We found 15 RS surveys published in relevant venues and journals between 2004 and 2016. However, only 7 out of these 15 surveys, published between 2012 and 2014, relate to the improvement of RS through the incorporation of context information. Aiming at providing a comprehensive understanding of the state of the art of this field, our SLR not only follows a well defined research methodology, but also characterizes CARS along all application domains, context types, and techniques reported in the studied literature. Most importantly, we documented the recommendation processes followed by content-based and collaborative filtering CARS, to characterize how these systems exploit context information along all phases of the process. The characterization includes recommendation techniques, paradigms for incorporating context, context types, application domains, and a detailed explanation of the mechanisms used to exploit context. We also compiled a catalog of datasets and validation methods used in the studied approaches, as well as a list of open challenges.

Table 1 compares our literature review (last row) with the most relevant CARS surveys we found in the state of the art. This comparison is based on seven criteria that we define as follows: *i) SLR*, the literature review follows a systematic methodology; *ii) not focused on particular domains or techniques*, the survey reviews the state of the art across all identified domains and techniques; *iii) not focused on particular context types*, the survey reports the exploitation of different context types; *iv) identifies context exploitation techniques*, the survey reports the ways how context was exploited

in the studied RS; *v)* *context in the stages of the recommendation process*, the literature review documents how context is exploited along the stages of the recommendation process; *vi)* *datasets*, the survey lists the datasets used by the studied systems; and *vii)* *validation techniques*, the review reports the techniques used to evaluate the studied approaches. The plus sign in a cell indicates that the survey is compliant with the corresponding criterion, whereas the absence of the sign indicates that it is not.

Table 1: Related work—Comparing our SLR with other surveys on CARS

Author/Year	SLR	Not focused on particular domains or techniques	Not focused on particular context types	Identifies context exploitation techniques	Context in the stages of the recommendation process	Datasets	Validation techniques
Verbert et al., 2012 [19]			+	+			+
Kaminskas and Ricci, 2012 [21]			+	+			+
Liu et al., 2013 [22]			+				
Champiri et al., 2014 [23]			+	+			
Campos et al., 2014 [24]		+					+
Inzunza et al., 2016 [25]	+	+	+				
Seifu and Mogalla., 2016 [26]		+	+				
Our literature review	+	+	+	+	+	+	+

According to Table 1, four surveys focus on particular domains: learning processes [19], music services [21], digital libraries [23], and mobile applications [22]. All surveys identify the different types of context exploited in the studied RS, except the one by Campos et al. [24] that focuses on time context only. Furthermore, this survey does not provide insights on the exploitation of context into RS (context exploitation techniques are not identified), but on the evaluation methods used to evaluate the effectiveness of CARS. The surveys conducted by Verbert et al. [19], and Kaminskas and Ricci [21] describe the techniques used to exploit context in the studied systems and the means used to validate them. However, they focus on particular domains. The survey by Liu et al. [22] focuses only on methods to identify the relevant context and the context types exploited in mobile systems. Thus, besides being do-

main specific, it does not report on techniques used to take advantage of context. As our literature review, the survey conducted by Inzuza et al. [25] follows a systematic approach and does not relate to a particular application domain, technique or context type. However, it does not report on context exploitation techniques. Also similarly to our work, the work conducted by Seifu and Mogalla [26] aims at characterizing the process followed by CARS in the form of what they call “*a framework of CARS*.” Nevertheless, their focus is not the way how context is incorporated and exploited, and the explanation of the framework in their six page paper is not as comprehensive as our characterization. Finally, none of the studied surveys report on the used datasets or relate context and its means to exploit it to the concrete phases of the recommendation process.

4. Methodological aspects

We conducted this study by following the guidelines proposed by Kitchenham and Charters in [12]. With our long-term research goal in mind—*to look for innovative and more effective ways of exploiting context information to improve the effectiveness of recommender systems*, we defined the set of research questions that would allow us to understand the state of the art of CARS. These questions are stated as follows:

- RQ1: How is context information exploited along the recommendation process?
- RQ2: What are the existing techniques used to incorporate context information into RS? For each technique, what are the most common application domains?
- RQ3: Is there any correlation between techniques used to incorporate context into RS and any of the traditional recommendation approaches (i.e., content-based, collaborative filtering and hybrid)?
- RQ4: What are the types of context more commonly exploited by RS? What techniques apply in each case?
- RQ5: What evaluation methods have been used to validate the effectiveness of CARS? What are the most common metrics used by these methods?

To answer these research questions and understand the way how context information is integrated into recommender systems, it was important first to characterize the processes that are followed by these systems, in particular by content-based and collaborative filtering approaches. That is, to understand the data that constitute the inputs, and the stages implemented by each type of recommender system to generate recommendations. This process-oriented characterization allowed us not only to report the techniques and context used by the studied RS, but also to map them to specific phases of the recommendation process, with the goal of leveraging the usefulness of this SLR for understanding the state of the art of this field.

We conducted a bibliographic search of conference proceedings and journal papers published in IEEE, ACM, ScienceDirect, EBSCO and Springer. These databases were selected because of the quality of their publications, and their relevance to RS. We used the search string (*("recommendation systems" OR "recommender systems" OR "recommendation" OR "recommendations") AND ("context aware" OR "context-aware" OR "context information" OR "contextual information" OR "location" OR "social" OR "time" OR "activity" OR "task" OR "environmental")*).

To select the papers to be included in the study we applied four filters: i) *publication date*, we selected papers published between 2004 and 2016; ii) *publication type, number of citations and language*, we excluded workshop and symposium proceedings, papers with less than 10 citations (with some exceptions for papers recently published) and non-English papers; iii) *relevance*, we studied the abstracts to verify the relevance of each paper. After this third filter, we obtained a total of 286 articles, including surveys on RS.

We thoroughly analyzed all these 286 articles and characterized those proposing CARS according to seven criteria: i) *recommendation system approach*, whether it is content-based, collaborative filtering, or hybrid; ii) *recommendation techniques*, the mechanisms used at the different stages of the recommendation process; iii) *paradigm for incorporating context*, whether it is pre-filtering, post-filtering, or contextual modeling; iv) *context types*, the context categories that are exploited in the recommender system (based on the classification proposed by Villegas and Müller [5]); v) *application domain* (if applicable), the specific area targeted by the proposed RS; vi) *evaluation*, the methods and metrics used to validate the effectiveness of the proposed RS; and vii) *data sets* (when reported), the data used to evaluate the proposed approach.

The fourth and last filter consisted in excluding those papers for which we could not identify any of the mandatory criteria presented above. The final set of papers includes 87 manuscripts that propose CARS and 15 surveys, including four highly relevant papers that were published in 2017.

5. Characterization of Context-Aware RS (CARS)

This section summarizes, for each type of recommender system, the findings of our SLR. We consider that the differences between content-based, collaborative filtering, and hybrid recommenders are too profound to analyze them all together, thus we set to do it independently.

To characterize content-based and collaborative filtering CARS, we first represented their recommendation processes using flow diagrams (cf. Figs. 1 and 2) that allow us to distinguish the different phases they comprise, and identify the points where context information is exploited by the surveyed RS, following either the pre-filtering, post-filtering or contextual modeling paradigms.

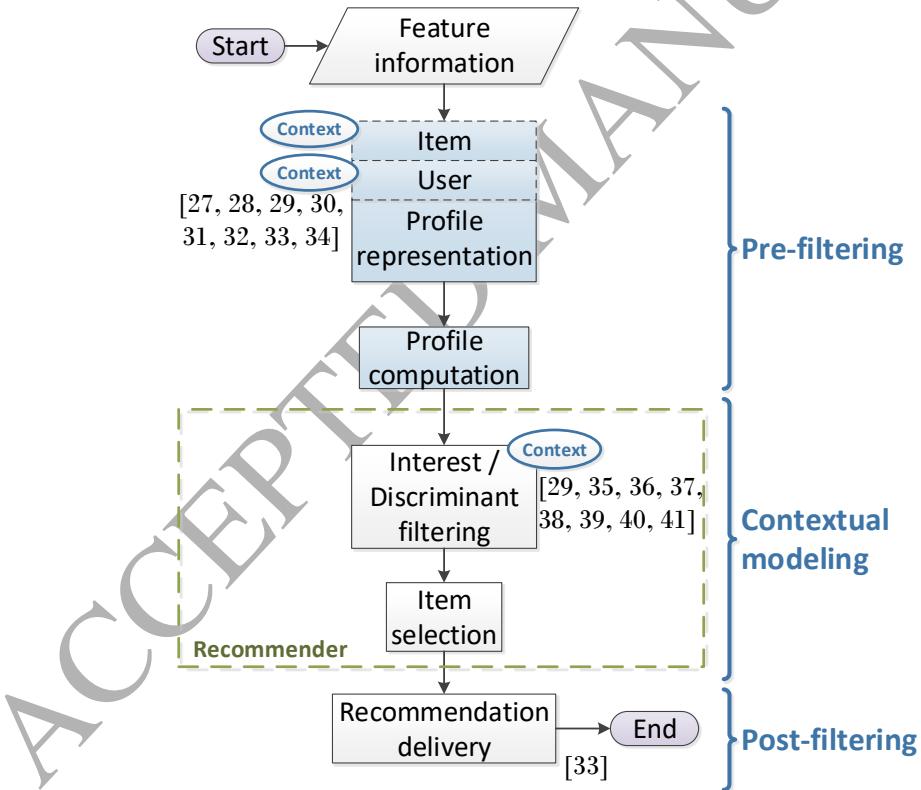
Bold ovals labeled as “Context” indicate the points of the process where we consider that context information can be incorporated. Citations next to each oval correspond to the studied approaches that integrate context in that specific phase of the recommendation process. The absence of citations next to an oval indicates that although we consider context can be exploited at that phase of the process, we found no approaches that do so. Furthermore, each brace depicted in the diagrams groups the stages of the process associated with each of the three paradigms commonly used to incorporate context into a CARS (i.e., pre-filtering, contextual modeling and post-filtering).

It is important to stress out that we focus on the ways in which context can be incorporated and exploited in the recommendation process. Even though on the diagrams we illustrate that process as a whole, we are mainly interested in showing the specific points where the reviewed papers (their references are placed accordingly on the diagrams) decided to adapt the recommendation process to exploit context. While we rely on some of the reviewed papers to illustrate the characterization and findings presented in this section, a more detailed retelling on how each paper implements their system and incorporates context can be found on Tables 2 and 3.

5.1. Content-based approaches

We found 15 papers associated with content-based CARS. Table 2 summarizes the characterization of these papers (cf. Column *Appr.*), which is driven by the process depicted in Fig. 1. Columns *Profile representation*, *Profile computation*, and *Discr. filter* indicate the techniques implemented by the studied systems to realize the main phases of the content-based recommendation process. Column *Paradigm* denotes the strategy used to incorporate context information: pre-filtering, contextual modeling, post-filtering. Column *Context Types* corresponds to the context categories exploited by the corresponding approach. Column *Domains* lists the application domains for which the RS was proposed. The last column explains the means used by the studied CARS to exploit context information.

Figure 1: Process followed by content-based CARS



5.1.1. The beginning of the process

The process implemented by content-based CARS (cf. Fig. 1) begins with the identification of the features in the available data that will define the common dimensional space used to describe item characteristics and user preferences (cf. *User profile definition* and *Item profile definition* in Fig. 1).

Pre-filtering strategies are applicable through the incorporation of contextual factors in the definition of item and/or user profiles. These strategies reduce significantly the search space for the discriminant filter by initially discarding a part of the information available. However, they require the inclusion of redundant user or item profiles for different contextual situations.

All content-based reviewed papers defined the features used as the basis for their recommendation, but only about half of them included contextual information as features. CARS proposed in [27, 28, 29, 30, 31, 32, 33, 34] exploit context using a pre-filtering strategy to generate different contextual *user* profiles for the same user, with different preferences for different situations (see Table 2 for more details regarding the four papers that apply pre-filtering as the paradigm to incorporate context). For instance, [29] proposes a movie CARS where contextual variables of different types such as time (weekday, weekend), location (theater, home), and social context (companion, friends, family) are taken into account to consider or ignore past user ratings, by building several context-aware (micro) profiles that are used to generate context-aware recommendations. As a result, the same user can have different profiles.

None of the surveyed papers associate contextual information with items. We assume that this is because it is easier to think in terms of contextual user profiles than in terms of contextual item profiles, probably because user preferences naturally vary according to context situations. Still, it is completely possible to have different *item* profiles for different situations. Nevertheless, since very often the number of items is many times larger than the number of users, it would mean increasing the complexity of the recommendation process given that a considerably larger number of items must be handled by the system.

5.1.2. The core of the process

The next phase is the core of the recommendation process. In general, a discriminant filter working as a utility function between user and item profiles is responsible for generating a recommendation score from the item and user vectors. This can be done through several strategies: i) by applying

some similarity measure such as *Cosine Similarity* (since items and users are represented on the same dimensional feature space, it is possible to compute the distances or similarities between them, with the goal of selecting the items closer to the user's preferences [27, 28, 29, 30, 31, 34, 35, 36]); ii) by obtaining a given classification score by applying a supervised learning technique ([37, 38, 39]); or iii) by applying a heuristic approach (context information can be considered into a discriminant filter, not as additional profile dimensions, but as an integral part of the function definition [32, 33, 35, 40, 41]). Either way, the recommender engine will associate a numeric value to each item, order the items accordingly, and select the ones that appear at the top or that surpass a specified threshold.

At this stage of the process, contextual information can be incorporated by influencing the similarity or distance between items and users. For example, [36] proposes a music recommendation system that incorporates the time at which users accessed different items (songs) in order to provide more relevant recommendations. In their system, users are described by a vector of their correlations to the considered time-related contexts (dawn, morning, monday, tuesday, spring, christmas), items are described as a vector of their correlations to the domain features (e.g., band, genre) as computed by a TF-IDF measure, and the historical accesses to items by users are kept as a collection of pairs of vectors as previously described. To perform a recommendation, the cosine similarity measure is applied to the user's current context and the historical accesses, the similarity of the historical accesses to the items is computed, and an aggregation of both measures allows the scoring of every available songs, so that the top five songs are presented to the user.

5.1.3. The end of the process

Finally, the selected recommendations are organized and delivered to the user. Post-filtering strategies apply at this stage to eliminate the recommendations that are irrelevant to the user's current context. We found that only the RS presented in [33] applied this paradigm to filter out movie recommendations that did not correspond to the current time and location.

5.1.4. Findings

Regarding the paradigm used to incorporate context into the RS (cf. Sect. 2.2.2), findings show that content-based approaches use contextual modeling as much as pre-filtering (one of those combining both strategies);

both paradigms being followed by 53% of the papers. Only one of the studied content-based CARS [33] incorporates context information using post-filtering, combined with pre-filtering. We hypothesize that this may be in part because post-filtering strategies may result in wasting time and computational resources, since the obtained recommendations may become useless after evaluating them with respect to the current context of the user, which is taken into account only at the end of the process. Indeed, pre-filtering approaches provide more benefits in what respects to computational complexity, and contextual-modeling solutions have proven to be more effective for the accuracy of recommendations [4].

With respect to the types of contextual information commonly used in the reviewed systems, and their application domains, we found that time context is commonly used in application domains such as movies and news; location context, in domains associated with movies, music and points of interest; activity context in domains related to movies, music and points of interest; social context in multimedia applications and human context in web services recommendations. It is of particular interest that none of the reviewed content-based CARS target the e-retailing domain, an otherwise popular application domain in traditional RS.

Table 2: Characterization of content-based approaches

Appr.	Profile representation	Profile computation	Discr. filter	Paradigm	Context types	Domains	Means to incorporate context
[28]	Item features	Case based reasoning (CBR)	Cosine similarity	Pre-filtering	Time, Location, Activity, Artificial (environment)	Movies, Music, News	Generates a contextual user profile by revising the user's consumption behavior. Then, it uses cosine correlation to measure the similarity between the user contextual profile and the item profile.
[37]	Item features	Heuristic approach	Decision tree algorithm	Cont. Model.	Activity, Human (age, gender)	Indoor Shopping, Points of interest	Proposes a framework where the relationship between user profiles and services under the same context situation are analyzed to infer user preference rules, using the decision tree algorithm.
[27]	Item features structured by a reference ontology	Heuristic approach	Cosine similarity	Pre-filtering	Activity, Time, Location	Movies	Tracks user browsing behavior, and understands user preferences in each particular context. Then, it performs recommendations by means of an aggregation agent that selects the top N items with the highest inferred values.

Table 2: Characterization of content-based approaches

Appr.	Profile representation	Profile computation	Discr. filter	Paradigm	Context types	Domains	Means to incorporate context
[30]	Tag-based features	Heuristic approach	Cosine similarity	Pre-filtering	Time, Location, Activity, Natural (Weather)	Points of interest	Uses a relational Markov network to match the features of Points of Interest (POI) with the current context. POI's features (e.g. outdoor seating, waiter service, dinner) are taken as the inputs to a neural network used to classify the appropriate level of interest (5 categories) of the user for the POI, under the given context situation. The resulting vector that characterizes the POI is then compared to the user vector using cosine similarity.
[29]	Item features	Heuristic approach	Cosine similarity	Pre-filtering, Cont. Model.	Time, Social, Location	Movies	Pre-filtering: Splits user ratings according to the contextual situation in which the preference is expressed, then builds several context-aware (micro) profiles used to infer preferences for new products. Contextual Modeling: Considers context as a weighting factor that influences the recommendation score of a user for a certain item. It combines the non-contextual vector space representation of user preferences with a vector space representation of context, which is built using the pre-filtering approach.
[35]	Latent semantic features	Term frequency inverse document frequency (TF-IDF)	Cosine similarity	Cont. Model.	Location	News	User is defined by the articles read in the past along with his/her location. The system seeks to rank a set of articles that satisfy the geographical location of the user. The preference score is determined by a cosine function ($f(a, l)$) that measures the appropriateness of each article a to a location l .
[38]	Item features	Heuristic approach	Joint probabilistic distribution	Cont. Model.	Activity	Music	Formulates the context-aware recommendation of songs as a two-step process: i) infers the user's current situation category given some contextual features sensed from a mobile phone, and ii) finds a song that matches the given situation. The first part computes a probability distribution using the Bayes' rule. The second part computes a prior probability that captures the history of user preferences.
[40]	Item features	Heuristic approach	Heuristic approach	Cont. Model.	Location	Indoor shopping	Focuses on mobile recommender systems for assisting indoor shopping by considering location-context. User preferences are calculated through a heuristic approach that integrates three factors: i) time spent in a brand store, ii) frequency of visits to the store, and iii) the matching between the special offers or promotional activities done in the brand store and the user's preferences.
[36]	Item features	Term frequency inverse document frequency (TF-IDF)	Cosine similarity	Cont. Model.	Time	Music	Context refers to the time at which the user listens to a song. The approach predicts user preferences by: i) computing the similarity between the user's current and historical contexts, ii) computing the correlation between historical context and an item, and iii) deriving the expected preference by multiplying measures obtained in i) and ii).

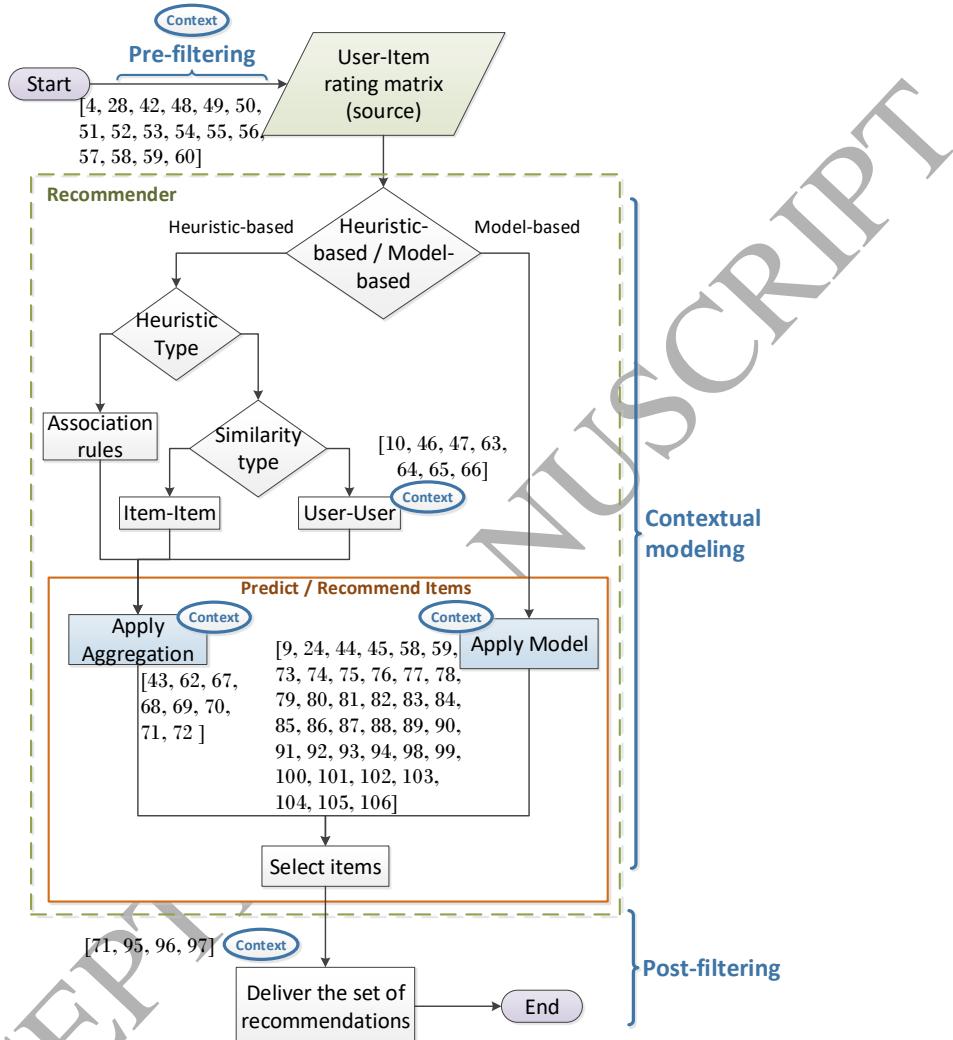
Table 2: Characterization of content-based approaches

Appr.	Profile representation	Profile computation	Discr. filter	Paradigm	Context types	Domains	Means to incorporate context
[39]	Latent semantic features	Heuristic approach	Joint probabilistic distribution	Cont. Model.	Activity, Location	Music	Implements a recommendation model where a set of latent topics is used to associate music content with a user's music preferences under certain location. It is based on the joint probability distribution of user, place, song and lyrics. The latent topics are the intrinsic factors that explain why users prefer certain pieces of music in a particular location and during a specific time period.
[31]	Item features	TF-IDF	Cosine similarity, Jaccard similarity	Pre-filtering	Human (user-interest)	Web services	Infers user preferences from the description of the web services that have been accessed by the user.
[32]	Item features	Heuristic	Heuristic	Pre-filtering	Social (followers)	Multimedia	Utilizes Social context (followers) as the basis to decide on user-similarity.
[41]	Item features	Heuristic	Heuristic	Contextual modeling	Location	Points of Interest	Considers context as a weighting factor that influences the recommendation score of a user for a certain item.
[33]	Item property	Heuristic	Heuristic	Pre-Filt, Post-Filt.	Location, Time	Movies	Recommends items with a composite structure (movie theater + movie + showtime). This approach first computes a similarity metric that concerns to the relation between the composite item (theater, movie, showtime) -Pre-Filtering. Then, this similarity measure is incorporated into the discriminant filter -Post-Filtering.
[34]	Item feature	Heuristic	Euclidian Distance	Pre-filtering	Activity	General application	Utilizes a sequential patterns method to find rules from data records on users' smart-phones. Then, by detecting and matching the user's current situation to the rules, which consider his current context and the events in which he has participated, the system determines the most suitable rules for making just-in-time recommendations.

5.2. Collaborative filtering approaches

Figure 2 depicts the general process followed by collaborative filtering CARS. Based on this process, we characterized the 69 collaborative filtering CARS studied in our SLR. This characterization is summarized in Table 3. Column *Recommendation strategy* presents the techniques implemented by the studied approaches, which can follow different paths of the recommendation process, as explained later in this section. As in the characterization of content-based CARS (cf. Table 2), the characterization of collaborative filtering CARS includes the paradigm used to incorporate context into the system (cf. column *Paradigm*), the types of context information exploited by the studied approaches (cf. column *Context Types*), the application domain (cf. column *Domains*) and the mechanisms used to exploit context (cf. column *Means to incorporate context*).

Figure 2: Process followed by collaborative filtering CARS



5.2.1. The beginning of the process

The input of the collaborative filtering process is a user-item rating matrix, where usually rows represent users, and columns represent items. This matrix can include additional dimensions to represent contextual information in the form of synthetic columns or rows, as in the case of the systems presented in [4, 42, 43, 44]. For example, Baltrunas et al. [42] extend the

user-item rating matrix into a user-item-context matrix, where contextual information consists in categorical tags (e.g. sunny, cloudy, raining) associated with a given rating.

Depending on the application domain, this matrix can be either obtained directly from the interactions of users with items (e.g., by capturing media accesses instantly [28, 45, 46, 47]), or inferred from historical interactions stored in transactional databases (e.g., by analyzing event logs of previous accesses to the recommended items [10, 48]). This matrix can be very sparse and its processing can be computationally challenging when the number of users and items is considerable (several hundreds of thousands).

At the beginning of the process, *pre-filtering* strategies generate different contextual user-item rating matrices, independent of each other. On the one hand, pre-filtering strategies reduce computational complexity since only a portion of the rating matrix is considered; on the other hand, they imply an extra effort in the acquisition of information, since ratings must be generated for every contextual situation that remains relevant after applying the filter.

We identified 16 papers reporting on the application of context-based pre-filtering strategies to generate recommendations [4, 28, 42, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60]. Pre-filtering is a simple strategy that discards a large part of the data to be analyzed, according to the user's current context. An instance is the process followed by the CARS proposed by Lee et al. [48], in which the authors analyze the access logs to songs, and extract context from the timestamps. Then, they define fuzzy membership functions to fuzzy sets for different contextual variables such as season, time of day, or day of the week, in such a way that the same song recommended at different moments is not considered to be the same item. Another example of collaborative-filtering pre-filtering CARS is the one proposed by Baltrunas et al. [42]: if a statistical test shows that context affects the consumption of an item, they split the item into several synthetic items according to the context situation. For instance, a movie could be split into the same movie associated with winter time, and another one associated with summer time.

5.2.2. The core of the process

To perform the actual recommendation, we identified that most systems apply one of two types of collaborative filtering approaches: *heuristic-based* and *model-based* methods. We found no relationships between any of these methods and particular application domains.

Heuristic-based methods. In the studied systems, heuristic-based approaches are realized through association rules, or the analysis of similarities between users or items. The Apriori algorithm [61] is a common technique for association rule learning. First, it identifies the frequent individual items in the database. Then, it extends them to larger itemsets as long as those appear often enough in the database. Finally, these itemsets are used to determine association rules that allow the discovery of hidden relationships in the data, based on the conditional probability existing between itemsets. The association rules approach is mainly applied to transactional data. However, it can also be applied to the user-item rating matrix, by considering each user row as a single transaction.

An interesting finding of our SLR is that despite approaches such as the one reported in [62] mine association rules, none of the studied systems exploit this technique to incorporate context. A reason for this could be that it would imply extra efforts to acquire the information required to generate a more comprehensive rating matrix, such that the extracted rules are meaningful enough in terms of support, and include context in rule antecedents.

Heuristic-based approaches based on similarity analysis consist in determining the distance between users or items. Each user can be seen as a vector in a feature space with an independent dimension associated with each item (and vice-versa). In general, these distances are determined using neighbourhood or clustering-based methods.

These methods work in two ways. The first one, user-user collaborative filtering, consists in inferring user preferences by determining the group of users that are more similar to the target user, and aggregating the items that are most popular among the members of the user group. The second one, item-item collaborative filtering, consists in determining the similarity among items rated by similar users. In either case, the method requires the computation of the distances between users or items, which can be computationally demanding when dealing with a considerable number of users or items.

Seven of the heuristic-based approaches included in this SLR incorporate context through user-user similarity matching; for instance, the approaches presented in [10, 46, 47, 63, 64, 65, 66] incorporate context to the analysis of user-user similarities (more details can be found on Table 3). On the other hand, none of the heuristic-based approaches use item-item collaborative filtering to incorporate context. As discussed previously, we hypothesize that this is because it results more natural to associate context with users

than with items. Nevertheless, in some application domains (e.g., products that are mainly consumed in a particular time of the day), context can be effectively associated with items, in which case an item-item collaborative filtering method that incorporates context would be an appropriate strategy.

Continuing with the recommendation process based on heuristic methods, the information obtained from applying the selected method is aggregated to rank the items to be recommended. Eight of the reviewed papers correspond to collaborative filtering RS that incorporate context as additional factors in the aggregation function. In particular, by using a maximization function [43, 62], a sum of products [67, 68, 69, 70, 71], and probabilities [72]. For instance, Khalid et al. [62] combine the approximated time required to reach a restaurant, the road speed conditions and the distance from the user into a defined metric. Then, the restaurant maximizing this metric is recommended to the user.

Model-based methods. Model-based approaches rely mostly on latent factor models applied to the user-item rating matrix. As we have said before, we can interpret this matrix as either a multi-dimensional representation space where each user is a vector with each item as a dimension, or a multi-dimensional representation space where each item is a vector with each user as a dimension.

The idea of latent factors RS is to obtain a single multi-dimensional space where both users and items can be represented, side by side, through matrix decomposition techniques. In this latent space (usually of smaller dimensionality than the user-item rating space), it is then possible to compute similarities and distances between users and users, users and items, and items and items.

We identified that some systems introduce contextual factors as additional dimensions of the original matrix (e.g., [44, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83]), while some other include contextual information as additive biases on users and items, to affect the calculation of missing ratings (e.g., [9, 45, 84, 85, 86, 87, 88, 89, 90, 91, 92]). An example of the first group is presented in [73], where the authors perform contextual recommendations using tensor factorization. This technique stores the latent feature of users, items and context types in three different matrices. Then, ratings are calculated as the inner product of the latent feature vectors of the given matrices. As a case of the second group, we can consider the RS presented in [85], which performs context-aware recommendations by incorporating temporal changes into the

matrix factorization technique. In particular, this approach seeks to capture past temporal patterns over products and items to predict future behaviour, and thus infer preferences. A particular case is the approach presented by Liu et al. [93], which incorporates social context from a social network into the recommendation model by considering that users belonging to different social groups should have different hyperparameters to be used during the matrix factorization process.

It is important to note that despite the collaborative filtering recommendation process indicates that heuristic-based and model-based techniques are not commonly used together, the authors of papers [9] and [88] propose CARS where model-based and heuristic-based techniques are combined. For instance, in [9] user interactions are represented in the form of a social network graph, where each node represents a user, and arc weights correspond to the trust existing between users represented by adjacent nodes (i.e., social context). This approach uses a heuristic-based technique (i.e., graph theory) along with a model-based method (i.e., matrix factorization).

We found a few papers reporting on the application of other approaches. In particular, machine learning techniques, where context information is usually incorporated by implementing probabilistic models such as the Bayesian model [24, 94], or the usage of classifiers such as support vector machines [81, 82, 83].

5.2.3. The end of the process

Similarly to content-based CARS, at the end of the process a contextual filter can be applied to the resulting recommendations to eliminate those items that are irrelevant to the current context. We found four papers reporting on the incorporation of context as a post-filtering strategy to ignore [95], filter [72, 96, 97], or adjust [72, 96] the inferred recommendations.

For example, the systems reported in [72, 96] ignore context until a traditional collaborative filtering algorithm produces restaurant recommendations, which are then adjusted to the user's current context.

Table 3: Characterization of collaborative filtering approaches

Appr.	Recommendation strategy	Paradigm	Context types	Domains	Means to incorporate context
[4]	Heuristic-based, User sim: Cosine similarity, Aggr.: Sum of products	Pre-filt.	Time, Social, Location	Movies	Filter information according to the current context. A rating is computed for the given user and item, as an aggregation of the ratings of other similar users.
[48]	Heuristic-based, User sim: Cosine similarity, Aggr.: Sum of products	Pre-filt.		Music	
[49]	Heuristic-based, User sim: Cosine similarity, Aggr.: Top N (most important users)	Pre-filt.		Movies	
[50, 51]	Heuristic-based, User sim: Pearson correlation, Aggr.: Sum of products	Pre-filt.	Time, Location	Movies	Filter information according to the current context. A rating is computed for the given user and item, as an aggregation of the ratings of other similar users.
[52]	Heuristic-based, User sim: Pearson correlation, Aggr.: Sum of products	Pre-filt.	Location	Points of interest	
[28]	Heuristic-based, User sim: Pearson correlation, Aggr.: Sum of products	Pre-filt.	Location, Activity, Artificial (environment)	Movies, Music, News	
[53]	Heuristic-based, User & Item sim: K-medians, Aggr.: Maximum	Pre-filt.	Time	E-retailing	The authors propose a neighbor-based collaborative filtering approach. A similarity measure over human and time contextual factors provides the basis for estimating the neighborhood of both users and items that will be considered in the recommendation process.
	Heuristic-based, User & Item sim: Graph theory, Aggr.: Maximum				
[54]	Heuristic-based, User sim: Graph Theory, Aggr.: Maximum	Pre-filt.	Location, Social	Points of Interest	
[60]	Heuristic-based, User & Item sim: Cosine similarity, Aggr.: Sum of products	Pre-filt.	Time	Movies, Music	The authors propose a neighbor-based collaborative filtering approach. A similarity measure over human and time contextual factors provides the basis for estimating the neighborhood of both users and items that will be considered in the recommendation process.
[42]	Model-based, Tech.: Matrix Fact.	Pre-filt.	Time, Social	Movies	Splits items that have been rated under different context situations. This split is performed only if there is statistical evidence that under these context situations users rate items differently.
[55]	Model-based, Tech.: Markov Chains	Pre-filt.	Time, Activity	General application	Processes user historical logs to extract contextual features such as day, time range, and location. Then, it identifies common preferences under different contextual conditions. Finally, it makes recommendations based on distributions of user preferences.
[56]	Heuristic-based, User Sim: Graph theory, Aggr.: Sum of products	Pre-Filt.	Social	Music, E-retailing	Examines the context-aware recommendation as a search problem in the contextual graph.

Table 3: Characterization of collaborative filtering approaches

Appr.	Recommendation strategy	Paradigm	Context types	Domains	Means to incorporate context
[57]	Heuristic-based, User sim: Pearson correlation, Aggr: Sum of products	Pre-Filt.	Different types	General Application	Context information associated with users is exploited to infer individual user profiles and from these, the profiles of the groups.
[58]	Model-based, Tech: Matrix Fact.	Pre-Filt., Cont. Model	Location, Time	Hotels & Tourism	The original user-item rating matrix is divided into sub-matrices according to the temporal states. Then, each sub-matrix is factorized by considering location characteristics.
[59]	Model based:, Tech: Matrix Fact.	Pre-Filt., Cont. Model.	Location	Web services	Users and services are clustered into groups according to their location. These are then characterized according to their particular QoS features into a local user-service matrix. There is also a global user-service matrix where location is not considered. Matrix factorization is performed on the local and global matrices in a step-wise hierarchical linear process
[46]	Heuristic-based, User sim: Pearson correlation, Aggr.: Sum of products	Cont. Model.	Location, Time	Points of interest	Adopts an adjusted Pearson coefficient that computes similarities between users in different contexts. In order to do so, the approach defines a context similarity matrix that includes the coefficient between two users' current contexts for using an item. This coefficient is then incorporated into the aggregation function that computes the missing ratings.
[62]	Heuristic-based, User sim: Pearson correlation, Aggr.: Maximum	Cont. Model.	Location, Time	Points of interest	Recommends restaurants by computing the approximate time in reaching it, and considering distance, speed and road conditions. This approximation is included into the aggregation function.
[43]	Heuristic-based, Item sim: Cosine similarity, Aggr.: Maximum Heuristic-based, As. Rules: Apriori, Aggr.: Maximum	Cont. Model.	Location, Time	Points of interest, Music	Transforms the initial user-item matrix by integrating contextual factors as virtual items.
[67]	Heuristic-based, Item sim: Pearson correlation / Cosine Similarity, Aggr.: Sum of products	Cont. Model.	Human (mood), Time	E-learning	
[10]	Heuristic-based, User sim: Cosine similarity, Aggr.: Sum of products	Cont. Model.	Time, Human (intent of purchase: Personal-work, Gift Partner, Friend, Parent)	E-retailing	Considers virtual users under different contexts and finds neighbors of contextually similar users to infer recommendations.
[47]	Heuristic-based, User sim: Jaccard Similarity, Aggr.: Sum of products	Cont. Model.	Location, Time	Points of interest	Modifies the Jaccard similarity measure to incorporate context.

Table 3: Characterization of collaborative filtering approaches

Appr.	Recommendation strategy	Paradigm	Context types	Domains	Means to incorporate context
[63]	Heuristic-based, User sim: Pearson Coefficient, Aggr.: Sum of products	Cont. Model.	Social	General application	Integrates the strength of the relationships between telecom users into the similarity measure. This strength is modeled taking into account context information associated with phone calls such as duration, time of day and day of the week.
[9]	Model-based, User sim: Graph theory, Tech.: Matrix Factorization	Cont. Model.	Social	Movies	Combines the user-item rating matrix with user-user social contextual information from a trust network to generate a modified rating matrix. This last matrix is then factorized.
[84]	Model-based, Tech.: Matrix Factorization	Cont. Model.	Social	General application	
[85]	Model-based, Tech.: Matrix Factorization	Cont. Model.	Time	Movies	Consider context information to add biases on users and items into the recommendation model. Rating values are then influenced by context changes.
[45]			Time	Points of interest	
[86]			Time, Location	Movies	
[87]			Location, Time, Activity	Points of interest	
[91]			Social	Books, Music, Movies	
[92]			Social	General application	
[88]	Model-based, Tech.: Matrix Factorization	Cont. Model.	Time, Human (Hunger level, mood)	Food, Movies	Clusters items into groups according to the context of their consumption and treats them as virtual items associated with users in a new matrix that is then factorized. Missing ratings are inferred taken into account contextual information.
[89]	Model-based, Tech.: Matrix Factorization	Cont. Model.	Social	Books, Music, Movies	Considers context information to add biases on users and items into the recommendation model. Through matrix factorization, it creates a common latent factor space for users and items. In this representation space, users and items are clustered independently, so that they can then be brought back to a user-item rating matrix, where missing ratings can be inferred for groups of users.
[90]	Model-based, Tech.: Matrix Factorization	Cont. Model.	Human (age, gender)	Movies	Constructs several prediction models based on matrix factorization. Each model is then refined by taking into account the predictions from other models. Context information is considered to add biases on users and items into the recommendation model. Rating values are then influenced by context changes.

Table 3: Characterization of collaborative filtering approaches

Appr.	Recommendation strategy	Paradigm	Context types	Domains	Means to incorporate context
[73, 74]	Model-based, Tech.: Tensor Factorization	Cont. Model.	Time, Human, Social	Movies	Perform context-aware recommendations using tensor factorization, which considers the latent features of users and items, and the interaction of the user with an item under a given context. The latent feature of users, items and context types are stored in three matrices. Thus, the inference of preferences is computed as the inner product of the latent feature vectors of the matrices.
[75]			Time	Movies	
[76]			Location, Activity	E-retailing	
[77]			Social, Time	Movies, Food	
[78]			Social, Time	E-retailing, Movies	
[79]			Human (hunger level), Time, Location	Food	
[80]			Social, Time	E-retailing, Movies	
[81, 82]	Model-based, Tech.: Support Vector Machine (SVD)	Cont. Model.	Time, Social, Natural (weather), Location	Points of interest	Apply SVD to the ratings as represented in a user-item-context space to discriminate between recommended and not recommend items.
[83]	Model-based, Tech.: Support Vector Machine (SVD)	Cont. Model.	Location	Points of interest	
[94]	Model-based, Tech.: Bayesian Model	Cont. Model.	Time, Location, Human (mood)	Movies	By adopting a binary particle-swarm optimization technique, identifies the relevant contextual factors for user and item classes, and incorporates them into a latent probabilistic model.
[24]	Model-based, Tech.: Naïve Bayes	Cont. Model.	Time	Movies	Identifies which members of a household made some specific unidentified ratings of movies by considering time-context conditions such as hour of the day, day of the week and date of rating, as well as number of ratings given by a user. To do this, it analyses temporal trends using probability models.
[98]	Model-based, Tech.: Sparse Linear Method	Cont. Model.	Time, Location, Social	Movies	Models the contextual rating deviations of items, by assuming that there is a rating deviation for each <item, context condition> pair. This deviation is represented in a matrix, where each row represents an item, and each column represents an individual contextual condition. Then, the ranking score is estimated by an aggregation of user ratings on other items in the same context.
[99]	Model-based, Tech.: Linear Regression	Cont. Model.	Social, Time	Hotels & Tourism	Predicts user preferences using a linear regression model, which includes a value that represents the user context preference. This value can be computed by means of three different probabilistic methods: i) mutual information based method, ii) information gain based method, and iii) chi-square statistic based method.

Table 3: Characterization of collaborative filtering approaches

Appr.	Recommendation strategy	Paradigm	Context types	Domains	Means to incorporate context
[100]	Model-based, Tech: Matrix Fact.	Cont. Model.	Location, Social	Points of interest, Hotels & Tourism	Location of venues and user social network information are integrated into the matrix factorization model.
[64]	Heuristic-based, Item & User sim: Pearson correlation, Aggr: Weighted ad-hoc	Cont. Model.	Social	Web services	The level of trust among users (social context) is included in the weighted aggregation
[65]	Heuristic-based, User sim: Ad hoc, Aggr: Ad hoc	Cont. Model.	Location, Social	Points of interest, Hotels & Tourism	The social (relationships) and location context of the user is integrated into the process to measure the similarity between users.
[44]	Model-based, Tech: Matrix Fact.	Cont. Model.	Time, Activity, Location, Artificial	General application	Context-aware preferences as dimensions of the matrix
[93]	Model-based, Tech: Matrix Fact.	Cont. Model.	Social	E-retailing	Social context is considered in order to define groups of users with particular hyper-parameters used by the matrix factorization model
[68]	Heuristic-based, User sim: Cosine similarity, Aggr: Sum of Products	Cont. Model	Time, Social	General application	The prediction of user's preference is affected by the user-similarity , which is computed by considering the context (i.e, the social taggins)
[69]	Heuristic-based, User sim: Pearson correlation, Aggr: Sum of Products	Cont. Model	Time	Movies	Adds a time dimension to the original input data. It is defined in a new table which shows item ratings for an active user at different time-frames.
[70]	Heuristic-based, User sim: Cosine similarity, Aggr: Sum of products	Cont. Model	Time	Music	Infers user's preference by considering a context score, which is computed for each item in the recommendation list which shows the suitability of that item for the current context of the user.
[101]	Model-based, Tech: Random walk	Cont. Model.	Social	Social Networks	Tags from social networks are the basis for user similarity (Jaccard). Posts from users are compared by applying an ad-hoc similarity measure. A random walk algorithm is applied in order to estimate weights relating users to users in the social domain and users to items on auxiliary domains (web posts, videos, labels)
[102]	Model-based, Random walk	Cont. Model.	Time	Web services	Making time-aware personalized QoS prediction is important for high-quality web service recommendation because their performance is highly correlated with invocation time, since service status and network conditions are continuously changing. Time is integrated into a modified Pearson correlation similarity measure (similarities between users and between web services); time is also considered when making the final QoS prediction.
[103]	Model-based, Tech: Matrix Fact.	Cont. Model.	Social, Time	E-retailing	Social networking features of users (demographics, user posts, groups of related users, temporal activity preferences) that also interact with an unrelated e-commerce site can be transformed into latent factors that can be used for product recommendation, particularly for unknown new users of the e-commerce site.

Table 3: Characterization of collaborative filtering approaches

Appr.	Recommendation strategy	Paradigm	Context types	Domains	Means to incorporate context
[104]	Model-based, Tech: Matrix Fact.	Cont. Model.	Social	Retailing	The authors propose Social Poisson Factorization (SPF) probabilistic model that incorporates social network information into a traditional factorization method, assuming that each user's clicks are driven by their latent preferences for items and the latent influence of their friends (modeled as conditional probabilities). SPF also allows for generating explanations of recommendations based on the social relationships of users.
[105]	Model-based, Tech: Matrix Fact.	Cont. Model.	Social	Retailing	A probability based matrix factorization is proposed, taking into account trust relationships in a social network in the item recommendation process for retailing purposes. Users and items are then clustered using a Gaussian Mixture Model to enhance the recommendation performance.
[106]	Model-based, Tech: Matrix Fact.	Cont. Model.	Location, Social	Points of interest	The authors propose a probabilistic matrix factorization method which considers contextual information taken from a location-based social network, where each point of interest is described using a topic model, geographical and social correlations.
[66]	Heuristic-based, User sim: Jaccard similarity, Aggr: Heuristic graph based.	Cont. Model.	Social	Social Networks	The social features of folksonomies are used to provide a user with recommendations of similar users and resources. User profiles consider social contexts, by incorporating information of actions performed by the user on neighboring users' tags, and of other neighboring users on the user's tags. User neighborhoods are defined based on the social network friend relationships according to a specified length of the minimum path linking two users.
[71]	Heuristic-based, User-Sim: Ad-hoc, Aggr: Sum of products	Cont. Model.	Social	E-retailing	Adopts an ad-hoc similarity measure that computes similarities between users in different social context. This measure is then incorporated into the aggregation function that computes the missing ratings
[72]	Heuristic-based, User sim: Graph theory, Aggr.: Probability	Cont. Model., Post-Filt.	Time, Location, Natural (weather), Social	Movies, Hotels & Tourism	Proposes a graph-based contextual model framework. It examines the context-aware recommendation as a search problem in the contextual graph. It also includes a probabilistic-based post-filtering strategy to improve the recommendation results giving contextual factors.
[97]	Model-based, Tech: Matrix Fact.	Post-Filt.	Time	Movies	The authors propose two successive SVD matrix factorizations to further refine the latent factors for users and items independently, while using time context to filter out unfit items.
[95]	Heuristic-based, User sim: Cosine Similarity, Aggr.: Sum of products	Post-Filt.	Location, Time, Natural (weather)	Hotels & Tourism	Keeps track of contextual features of past user travels to each location. Context aware recommendations are inferred by finding the most similar users, calculating a score for each location, and filtering locations that do not meet contextual conditions.
[96]	Heuristic-based, Users sim: Pearson correlation, Aggr.: Sum of products	Post-Filt.	Time, Location	Points of interest	Adjusts inferred ratings to deliver contextual recommendations.

5.2.4. Findings

The information summarized in Table 3 suggests a correlation between the strategy used to generate recommendations and the paradigm used to incorporate context into the recommendation process of collaborative-filtering CARS.

In general, model-based approaches incorporate context using contextual modeling. This can be explained by the fact that models provide a more natural way to capture interactions between users, items and context. We also found papers reporting on the combination of model-based methods and pre-filtering strategies [42, 55, 58], or even the combination of the three strategies including contextual modelling [59]. However, these combinations may be risky since a pre-filtering strategy can cause loss of valuable information thus affecting accuracy [4].

Heuristic-based approaches are almost evenly distributed between the application of pre-filtering and contextual modeling strategies to realize context-aware recommendations. Regarding the application of pre-filtering, data sources are usually partitioned by context factors to improve data uniformity, which leads to stronger user/item similarities, as well as better confidence and support measures for association rules, thus improving the relevance of recommendations. In the case of contextual modeling, context information modifies how similarity is calculated.

With respect to contextual information, we found that most of the studied collaborative filtering systems have time, social, and location as the predominant factors. Furthermore, the application domains to which the surveyed systems are commonly applied are movies, restaurants, music, points of interests, social networks and e-retailing.

5.3. Hybrid approaches

Since hybrid approaches combine collaborative filtering and content-based recommendation methods in many different ways, there is not a unique abstract process that can characterize hybrid solutions the way we previously did for the non-hybrid processes depicted in Figs. 1 and 2. Table 4 presents the characterization of hybrid approaches, emphasizing on the way context is exploited.

As we found only five papers documenting hybrid RS, it is impossible to generalize their findings. Each approach follows its own strategy.

Table 4: Characterization of hybrid approaches

Appr.	Techniques	Paradigm	Context types	Domains	Means to incorporate context
[107]	Content-based Profile representation Item features	Pre-filt.	Time, Location	Movies, Music	Associate ratings with content-based attributes used to describe both user preferences and item features, and with the contextual factors gathered from the user experience (e.g., time of the day). Over the resulting vector space, the authors propose the application of several types of machine learning classification models.
	Collaborative filtering Model-based, Tech.: Naïve Bayes, Random forest, Multilayer Perceptron, and Support Vector Machine	Cont. Model.			
[108]	Collaborative filtering User sim: K-means	Pre-filt.	Location	Music, Points of interest	Takes into account user demographics: the geographical distance between the user and the event, and the subsequent time that it would take the user to arrive. It segments users into clusters, with every user having a probability of belonging to every cluster, and with each cluster having a probability distribution of liking every item. A discriminant filter evaluates the utility of the item for the user, considering a particular context.
	Content-based Profile representation Item features, Discr. filter Heuristic	Cont. Model.			
[28]	Collaborative filtering User sim: Pearson correlation, Heuristic-based Sum of products	Pre-filt.	Time, Location, Activity, Artificial (environment)	Movies, Music, News	Performs contextual recommendations by combining a discriminant filter with an aggregation of the ratings of similar users. A similarity measure between users takes into account their contextual profile.
	Content-based Profile representation Item features, Discr. filter Cosine similarity	Pre-filt.			
[109]	Content-based Profile representation: Item features	Cont. Model.	Social	Web Services	Identifies a couple of reading “experts” whose opinions can be regarded as guidance for news recommendation to particular individuals. Further, integrates this “expert” model with the content information and collaborative filtering, and propose a hybrid recommendation framework.
	Collaborative filtering Model-based, Tech: Matrix Factorization	Cont. Model.			
[110]	Collaborative filtering Model-based	Cont. Model.	Social, Location, Time	Social Networks	Social context is taken into account by considering the groups to which users belong to on an events-based social network. Users and events are described by the hour at which users attend events (time), and are compared by applying cosine similarity. Geographical preference of events is modeled by obtaining a probability density per user, taking into account the densities of attended events.
	Content-based Profile representation Item features, Profile comput. TF-IDF Discr. filter Cosine similarity	Pre-filt.			

5.4. Findings in the exploitation of context information

Figure 3 summarizes general findings related to the exploitation of context by the systems described in the surveyed articles.

Figure 3: Summary of findings in the exploitation of context information

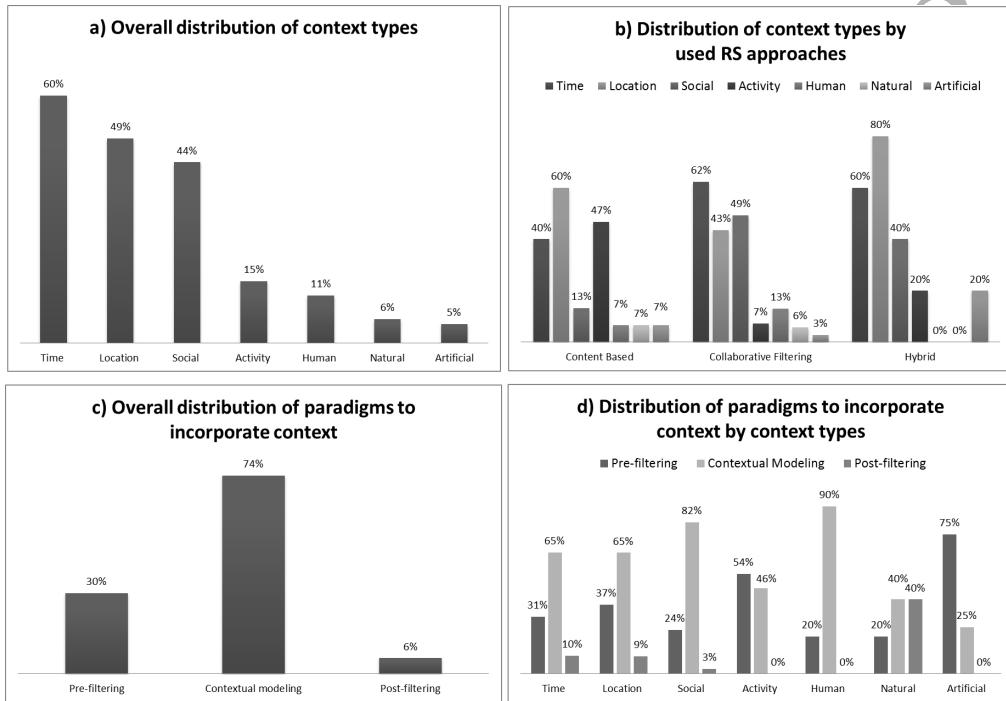


Figure 3.a presents the overall distribution of context types. According to this chart, time is the most used context factor followed by location and social information, whereas artificial is the less exploited context type followed by natural, human and activity. In the studied approaches, artificial context refers to data gathered from mobile sensors, natural context refers to weather conditions, and human context corresponds to user age, gender, mood, intent of purchase, preferences and hunger level. Only papers exploiting social context comment on the reasons why the exploited context type was selected. We hypothesize that, besides being relevant in all application domains, the main reason why time is the most exploited context type is that it is the easiest one to acquire: every system records information about transaction

dates, without requiring the explicit approval of users. As time context, location is also highly relevant and easy to acquire, however, its acquisition and usage, as in the case of social, activity and human context, requires user explicit approval. Artificial context does not necessarily compromise user privacy, however, its acquisition requires physical sensing infrastructures that are not always available.

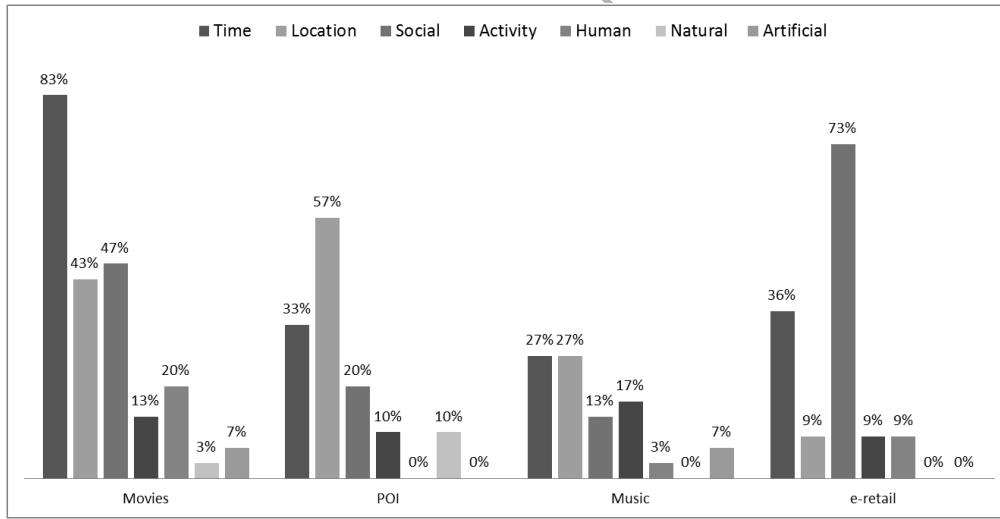
Regarding the context types used with the different recommendation approaches (i.e., content-based, collaborative filtering and hybrid), it is important to highlight that (cf. Fig. 3.b): i) only 13% of the content-based RS exploit social context. This is expected since social context emerges from the relationships among users, which are less relevant in content-based approaches; ii) location and activity are the most used context types in content-based RS. A reason for this is that the relationships existing between users and items usually emerge from the place where the item is used or bought, and the activity the user is performing while using an item. In addition, items are easily associated with places and activities; iii) time is the most exploited context type in collaborative filtering systems. This is probably associated with its easy acquisition, which becomes more relevant in collaborative filtering where it is required to characterize users under similar context situations; and iv) as expected, human context is more relevant in collaborative filtering than in content-based approaches, probably because demographic information is highly used in the analysis of user similarities.

Without doubt, contextual modeling, recognized by its effectiveness in improving the performance of recommendations, is the most common paradigm used to incorporate context into RS (cf. Fig. 3.c). Post-filtering, as discussed in previous subsections, is the less used, since its application may result on the discarding of time and space wise costly recommendations. Concerning the distribution of paradigms to incorporate context by context types (cf. Fig. 3.d), it is worth pointing out that systems exploiting activity (13 papers) and artificial (4 papers) context have pre-filtering as the predominant paradigm to incorporate context.

Most popular application domains identified in the studied papers are movies (30 papers, 34%), points of interest (POI, 18 papers, 21%), music (15 papers, 17%), and e-retailing (11 papers, 13%). Other domains are hotels & tourism (6 papers, 7%), web services (5 papers, 6%), news (4 papers, 5%), food (3 papers, 3%), indoor shopping (2 papers, 2%), social networks (2 papers, 2%), and e-learning (1 paper, 1%). Seven of the studied papers do not report targeting particular application domains (general application).

Figure 4 presents the distribution of context types by application domains. Movies is the only domain that exploits all context types, being time, social, and location the most exploited ones. As expected, location is the most common context type in the points of interest domain, followed by time. Concerning the music domain, location, time and activity are the most used context types. Activity is more predominant in this domain than in the others, probably because music genres are commonly associated with specific user activities. In the e-retailing domain, social is the predominant context type, followed by time. Here it is evident the influence of collaborative filtering as the predominant type of recommendation algorithm, particularly in this domain. Context types location, activity and human are equally exploited in e-retailing applications. Finally, it is worth also noticing that natural context, which in general refers to weather conditions, is more used in points of interest applications.

Figure 4: Distribution of context types by most popular application domains



6. Characterization of validation methods

The improvement of user experience is the ultimate goal of a recommender system. In order to measure it, a series of properties, each with

a set of metrics, have been proposed and used since the first developments in the field. These properties allow us to determine the pertinence of the recommendations being suggested. Instances of these properties are predictive power, confidence, diversity, learning rate, coverage, scalability and user evaluation [111].

In this section we summarize the properties that were considered to evaluate the recommendation systems documented in the surveyed papers, particularly predictive power, which is the most commonly used evaluation property. The first two parts of this section focus on prediction metrics and evaluation protocols identified in the studied articles. Then, we summarize other properties that were also used to assess the quality of recommendations in the studied CARS. Finally, we present the list of datasets that we identified in our survey.

6.1. Prediction metrics

Among the different metrics that can be considered to evaluate RS, the most commonly used is predictive power. This could relate to the information retrieval origins of RS. All but five of the papers we surveyed use some kind of prediction metric to assess the quality of their recommendations.

Table 5 presents the distribution of the reviewed articles with respect to prediction metrics. The first column represents the class of metric. The second column refers to the specific prediction metric techniques, grouped by their class. The third column presents the number of papers that use the metric to validate the proposal, which are listed in the last column. It is important to note that some articles may use more than one prediction metric to evaluate their approach. We borrowed the definitions of these metrics from [111] and [112].

Prediction metrics are based on different types of comparisons between the recommended items and the accessed or consumed items. As mentioned in [111], there are three classes of prediction metrics: rating prediction, usage prediction and ranking metrics (cf. first column of Table 5).

Table 5: Metrics used to evaluate predictive power

Class	Prediction Metrics	#Approaches	Approaches' references
Rating prediction metrics	MAE	27	[4, 9, 42, 46, 47, 50, 51, 59, 63, 69, 73, 77, 79, 80, 84, 88, 89, 91, 92, 93, 96, 100, 101, 102, 103, 105, 106]
	RMSE	24	[9, 10, 47, 56, 71, 77, 78, 79, 80, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 100, 101, 105, 106]
Usage prediction metrics	Precision	43	[4, 10, 24, 27, 28, 29, 32, 33, 36, 39, 40, 41, 42, 43, 44, 47, 51, 53, 54, 56, 58, 60, 62, 63, 65, 66, 67, 70, 71, 72, 75, 80, 82, 83, 84, 95, 97, 98, 101, 103, 106, 107, 109]
	Recall	28	[4, 10, 29, 33, 40, 42, 43, 44, 50, 53, 54, 58, 62, 63, 65, 67, 70, 71, 72, 75, 82, 84, 97, 98, 101, 103, 106, 109]
	F-measure	10	[4, 10, 29, 33, 40, 43, 57, 62, 67, 97]
	AUC	5	[24, 60, 74, 103, 107]
	MAP	8	[24, 34, 55, 76, 79, 95, 98, 103]
	BR	1	[95]
Ranking metrics	NDCG or DCG	9	[30, 31, 35, 47, 57, 72, 74, 87, 110]
	Hit Ratio	6	[48, 68, 70, 74, 87, 99]
	MRR or CRR	3	[99, 103, 104]
	Map@K	1	[101]
	Rt10	1	[35]
	None or other type reported	5	[37, 45, 49, 52, 81]

Rating prediction metrics. These metrics measure the correctness of the recommendations in terms of their error. The two metrics we identified in the studied articles are *root mean squared error* (RMSE) and *mean absolute error* (MAE). These metrics measure the distance between predicted and real ratings. So, lower values of RMSE and MAE indicate a higher predictive power. Since RMSE squares the error, it tends to penalize large errors more heavily. The choice between RMSE and MAE is at discretion of the developer. For instance, in the movies domain, while in [85] the RS is evaluated by measuring the quality of suggestions using RMSE, giving more importance to larger differences between the predicted and real ratings, in [73] the evaluation is based on MAE, considering a linear approach to measure the errors.

Usage prediction metrics. These metrics are based on different types of proportions between recommended and consumed items, as determined

by the contingency table that compares them. The following are the usage prediction metrics that we identified in the surveyed papers:

- *Precision (or true positive rate)* measures the proportion of recommended items that result relevant to the users, that is, those recommended items that the user actually consumes. The CARS proposed in [39] is evaluated with respect to a context-free approach using this metric. This system exploits user location (i.e., a gym, the library, the office, the transportation system) to suggest appropriate songs. The results show that the proposed approach outperforms its baseline (e.g., a precision of 60% and 50%, respectively, in situations where the location context corresponds to the transportation system).
- *Recall (or sensitivity)* measures the proportion of consumed items that were correctly recommended, that is, the fraction of items relevant to the user that were suggested by the system. Recall and precision are usually considered together as two facets of the quality of the recommendation. An example is presented in [53], where precision and recall are used as the basis to show that the greater the cardinality of a set of recommended items is, the higher the value of recall is.
- *Specificity (or true negative rate)* measures the proportion of not recommended items that are irrelevant to the users. This metric was not directly used in any of the surveyed papers, but it is a basis for the definition of other metrics such as AUC, explained below.
- The *F-measure* family of metrics combines precision and recall, allowing for the comparison of different RS using a single metric. Adomavicius et al. [4] use this metric to compare the effects of taking into account independent context factors (i.e., social, time and location), or combinations of them, when predicting user ratings. The results showed that the segments theater-weekend (i.e., location-time), theater (i.e., location), and theater-friends (i.e., location-social) substantially outperform the standard methods in terms of F-measure. They also applied F-measure to show how their approach outperforms regular non-context RS.
- *AUC (or area under the curve)* is a more robust metric that considers the variations between the true positive rate (recall) and the true

negative rate ($1 - \text{specificity}$). The movie CARS published in [74] is evaluated using this metric.

- Other usage prediction metrics are refinements of simpler ones, such as *mean average precision* (MAP) [55], or *benefit ratio* (BR) [95]. The latter is defined as the ratio between the number of users who get an improved prediction and the number of users who get a deteriorated prediction.

Ranking metrics. These metrics assume that the utility of a recommended item is proportional to its position in the ordered list of recommendations produced by the RS. The ranking metrics used to evaluate the CARS included in our survey are the following:

- *Normalized discounted cumulative gain (NDCG)* and *discounted cumulative gain (DCG)* consider that highly ranked relevant objects give more satisfaction than poorly ranked ones. Biancalana et al. [30] use NDCG to compare their CARS performance with the performance of other approaches. They also study the effect on the quality of recommendations, as measured by NDCG, by taking into account different contextual factors separately. Biancalana et al. [30] and Hong et al. [53] argue that CARS produce better results when the number of items to recommend increases.
- *Hit ratio* measures whether a user's target choice appears in the top- K recommendation list. Generally denoted as Hit@ K , where K indicates the number of recommended items. Unger et al. [87] find that the use of latent context models provides a noticeable advantage over non-contextual models for almost every value of K . The advantage is greater with small values of K (i.e., ranging from 1 to 4), which means that the latent context model is highly capable of ranking a suggested recommendation according to the user's current context.
- *Mean reciprocal rank (MRR)* and *Cumulative reciprocal rank (CRR)* evaluate the ranking position of a user's target choice in the recommendation list. Chen and Chen [99] use CRR to evaluate recommendations that take into account location context.
- *Mean average precision (MAP@K)* considers the precision of the first K recommended ranked items. Every item on the list of ranked items

contributes to the MAP@K measure of the recommendation proportionally to its position, if they were indeed accessed/consumed by the user for which the recommendations were made. Jiang et al. [101] use this metric, along with other metrics (MAE, RMSE, Precision, Recall, F1 measure) to evaluate the performance of different configurations of their proposed model.

- *Rt10* averages the ratings of the top 10 recommended items. It is used specially in information retrieval. Son et al. [35] show, using the Rt10 metric, that news article recommendations are more effective when considering their particular geographical location.

Finally, from the five papers that do not report the usage of a particular prediction metric, two of them use other mechanisms to evaluate their models. For instance, to evaluate user satisfaction, Hong et al. [37] measure effectiveness and usability, whereas Baltrunas et al. [45] use a standard usability questionnaire. The approach presented in [81] is compared to a baseline model in terms of accuracy without reporting any metrics. However, these authors published the same model in [82] including a quantitative evaluation.

6.2. Evaluation protocols

This subsection presents the different evaluation protocols applied by the authors of the surveyed papers. These protocols define the way data sets are handled and partitioned into training and test sets to evaluate the quality of the recommendations. We found that in all reported cases context was consistently considered as a data set partitioning criterion, and that the baseline approach is usually a context-free RS, or a CARS that follows a different approach than the one being proposed.

Table 6 presents the distribution of reviewed articles with respect to evaluation protocols. The first column lists the evaluation protocols, the second column shows the number of papers that use the protocol to validate the proposed CARS, and the third column specifies each of the corresponding surveyed papers. Papers [33, 41, 56, 103] did not report on the used evaluation protocol.

Table 6: Evaluation Protocols

Evaluation Protocols	#Approaches	Approaches
Holdout or cross-validation	46	[9, 10, 28, 31, 32, 33, 39, 45, 48, 54, 57, 58, 59, 60, 62, 63, 65, 66, 67, 68, 69, 70, 71, 72, 75, 76, 78, 79, 81, 82, 84, 87, 91, 92, 93, 94, 96, 97, 100, 101, 102, 104, 105, 106, 109, 110]
K-fold cross validation	21	[4, 30, 34, 38, 42, 43, 44, 47, 51, 55, 73, 77, 80, 83, 86, 88, 89, 90, 95, 98, 107]
Hypothesis test	5	[27, 35, 40, 46, 99]
Bootstrapping	2	[4, 29]
Simulation	1	[64]
None reported	4	[33, 41, 56, 103]

Holdout or cross-validation. This is one of the most commonly used evaluation protocols. It consists in splitting the dataset into two sets: training (e.g. 70% of the data) and test (30%). The recommendation model/algorithm is trained using the first set, and evaluated using the second one. The training and test data can be obtained in different ways, depending on the application domain and the way context information affects the recommendations. For example, in [39], Cheng and Shen evaluate their music CARS by splitting the data set according to time and location context, before extracting the training and test sets.

K-fold cross-validation. This is a more sophisticated evaluation protocol that consists in partitioning the dataset into K equally sized groups of items called folds, to then perform a cross-validation evaluation process. One of the folds is chosen as the test set and the union of the other folds as the training set. This process is repeated K times, each time changing the fold used as test set. This evaluation protocol is used to evaluate the CARS presented in [42]: for each fold, the authors compute the MAE, precision and recall metrics, and average their results to then estimate the quality of their recommendation model. The CARS proposed in [86] and [4] apply independent recommendation processes for each relevant context. The authors evaluate the performance of these systems using K-fold cross-validation. This allows them to compare the predicted ratings for each context, and establish the contexts for which the recommendation is more accurate.

Hypothesis test. This protocol uses statistical inference. It is based on the computation of the statistical significance of the differences between the

compared CARS. In particular, it is useful to identify whether there is a significant difference between contextual and non-contextual recommendations. The CARS presented in [99] is evaluated using this protocol, where the hypothesis is that user preferences are influenced by contextual factors, and that the proposed recommendation algorithm is capable of capturing such influences. For example, user restaurant preferences may not be influenced solely by aspects such as food quality, value, and service, but also by contextual factors such as location.

Bootstrapping. This protocol relies on random sampling with replacement. That is, a subset of size N is taken from the original data set and then partitioned into training and test data. This process is repeated multiple times, considering always the whole original data set as the basis for the re-sampling. The estimation of the performances of the RS is finally aggregated from the results of each re-sample. For instance, Musto et al. [29] use a bootstrapping-based protocol proposed in [4]. This protocol consists in identifying different possibly overlapping subsets of the dataset based on context types (e.g., establishing a contextual segment composed of time context observations, or another one composed of location context observations). The authors extract 500 random re-samples from their dataset and split them by assigning 29/30th of the items to the training set and 1/30th to the test set. They use precision, recall and F1 as the metrics to evaluate the performance of their system with respect to the different contextual segments.

Simulation. When there is no dataset available upon which to perform the evaluation of the recommendation model, it is possible to generate an artificial synthetic dataset using simulation techniques, based on certain suppositions (e.g. normal distributions). Eirinaki et al [64] applied this method to generate a social network simulating trust relationships between users (social context), and the matrix relating users to items (in their case, web services).

6.3. Other properties

Predictive metrics measure how close predicted preferences are from user real preferences. However, predictive power is not enough to measure whether the recommendation was satisfactory, useful or effective to the users [112]. A recommendation system may be highly accurate, but only for those items for which a recommendation may result useless (e.g., products that the user buys very frequently).

Table 7 presents the approaches that consider properties other than predictive power to evaluate the proposed CARS. The plus sign in a cell indicates that the corresponding property is used to evaluate the CARS proposed in the paper represented by the row (cf. first column of the table). As in the case of the prediction metrics presented above, we borrowed the definition of these properties from [111] and [112].

Table 7: Other properties

Appr.	Learning rate	Confidence	Diversity	Novelty	Coverage	Scalability	Usability
[76]	+						
[98]	+						
[86]	+						
[90]	+	+	+				
[62]		+				+	
[94]			+		+		
[66]				+			
[53]						+	
[79]	+					+	
[99]	+						+
[30]							+
[27]							+
[38]							+

Learning rate. This property measures how fast an algorithm produces good recommendations. Learning rate is also associated with the parameter that determines how fast or slow a recommendation model will converge towards an optimal solution. We found that all of the CARS evaluated through this property are based on model-based strategies (i.e., matrix and tensor factorization, and linear regression), and exploit context information by implementing the contextual modeling paradigm.

Confidence. This property refers to the trustworthiness of the system predictions, and the extend to which they help users make more effective decisions. The work published in [90] uses this property to evaluate, under specific contexts, the quality of several prediction models based on matrix factorization,

Diversity. This property measures how dissimilar are the recommended items among them. It is defined as the opposite of similarity. Zhang et al.

evaluate the quality of their movie CARS in terms of diversity [90]. They argue that a good recommender system is the one that delivers considerable different recommendations, for example, films belonging to different genres.

Novelty. Based on the assertion that the relevance of a recommended item depends not only on its correctness, but also on its novelty. Nocera et al. [66] define an ad-hoc measure that takes into account whether the recommended items were already known to the user (e.g. accessed in the past).

Coverage. This property measures the proportion of items that the system recommends from the universe of available items. Not all of the available items are subject to be recommended. This is the case of collaborative-filtering RS for items that have not been yet consumed or rated by the users. Sitkrongwong et al. measure accuracy and coverage for different contextual factors [94]. They found that, since not every context applies to all items, it is possible to increase the coverage by ignoring some of the relevant contextual factors. Nevertheless, there is a trade-off between accuracy and coverage that can be mitigated by identifying the set of relevant contextual factors for each user and each item separately, instead of identifying the relevant contextual factors for the entire data set.

Scalability. This property refers to the computational capability of the recommender system to handle a growing amount of data. Khalid et al. address this property by storing and processing data on geographically distributed nodes [62]. Shi et al. measure scalability in terms of time complexity [79]. We did not find any relation between context and scalability.

Usability. This property measures the satisfaction of the user with respect to the ease of use of the RS. In [27], Hawalah and Fasli evaluate usability through a questionnaire that asks users to rate a set of statements, including some to evaluate the contextual nature of the system: i) *the items recommended to me matched my interests*, ii) *the items recommended to me took my personal context requirements into consideration*, and iii) *I was only provided with general recommendations*.

6.4. Data sets

Table 8 characterizes the 16 data sets that we identified as publicly available from 32 out of the 87 characterized papers. For each data set, we indicate the papers that use it, the domain, and the supported context types.

Table 8: Data sets identified in the SLR

Appr.	Domain	Brief description	Context types	URL
[73]	Movies	Information about movies, users and ratings.	Human (age, gender)	https://research.yahoo.com
[9, 50, 57, 60, 75, 78, 80, 90, 97]	Movies	MovieLens: information about ratings, users, and items (movies).	Human (age, gender, occupation), Time (day, month, year, hour, minute, second)	http://grouplens.org/datasets/movielens
[72, 86, 88, 94]	Movies	Data set collected for experiments using an on-line application for rating movies. Users fill in a simple questionnaire created to explicitly acquire the contextual information describing the situation during the consumption. It contains records of users, ratings and movies.	Time (season, day type), Location, Natural (weather), Social	http://students.depaul.edu/yzheng8/DataSets.html
[85]	Movies	Provided by the Netflix Prize. It contains records of ratings, users, and movies.	Time	http://www.netflixprize.com
[24]	Movies	CAMRa 2011s MoviePilot Dataset: contains ratings, users, and items.	Time	http://2011.recsyschallenge.com/dataset
[36, 48]	Music	Information about users, artists, bi-directional user-friend relations, and user-listened artist relations	Social, Time (day, month, year)	http://grouplens.org/datasets/hetrec-2011
[54, 58, 62, 65, 100, 106]	Points of interest, Hotels & Tourism	Data set acquired from FourSquare. It contains information places.	Location, Social	https://sites.google.com/site/yangdingqi/home/foursquare-dataset
[68]	General application	Information about users, tagged papers, and tags.	Time, Social	http://www.citeulike.org/faq/data.adp
[69]	Movies	Provided by the Comaq Systems Research Center. Ratings given by users to movies.	Time	http://www.research.compaq.com/SRC/eachmovie
[65]	Points of interest, Hotels & Tourism	Friendship network with information about locations and user check-ins (user, check-in time, latitude, longitude, location)	Social, Location	http://snap.stanford.edu/data/loc-gowalla.html
[57]	General application	Information of ratings given by users to jokes	Human (user preferences)	http://eigentaste.berkeley.edu/dataset/
[71, 91, 93, 105]	E-retailing	Information about reviews of products done by users	Social	http://www.trustlet.org/opinions.html
[70, 93]	E-retailing, Music	Information about reviews of products done by users	Social, Time	https://labrosa.ee.columbia.edu/millionsong/lastfm
[91, 92, 93, 105]	E-retailing, Books, Music, Movies	Information about user reviews and recommendation services for movies, books, and music	Social	http://socialcomputing.asu.edu/datasets/Douban

7. The effect of incorporating context into RS

When conducting an SRL on CARS, a natural question is the level of improvement of RS performance (e.g., in terms of accuracy) obtained from the

inclusion of a particular context type into the recommendation process. Nevertheless, answering this question results impractical, given the wide spectrum of recommendation techniques that can be combined with the different context types, through any of the three existing paradigms to include context information into RS. Furthermore, the performance of these systems vary depending on the used dataset and evaluation metrics, which make the results incomparable. For this reason, questions such as *what is the context type that provides the best results for improving recommendations in a particular context domain?* were not included in the set of research questions that drove the development of this SLR.

Despite the limitations to compare the effectiveness of particular context types, we surveyed the impact of incorporating context information into the reported systems. We found that only 36 out of the 87 studied articles quantitatively evaluate the obtained improvements with respect to baseline approaches (cf. Table 9). This constitutes an opportunity for this research community—formal validations and benchmarks of CARS are of paramount importance to advance this field. The systems reported in these 36 papers were all evaluated with respect to at least one baseline approach in terms of accuracy, through any of the metrics listed in Table 5.

Table 9 presents the improvements reported by these papers. For each approach (cf. Column *Appr.*) the table includes the types of context exploited by the corresponding CARS, the application domain, and the improvement obtained for each of the used metrics. The table groups accuracy metrics according to the three metric categories (i.e., usage prediction, rating prediction and ranking prediction), explained in Sect. 6.1. The goal of this table is to report the surveyed information rather than to provide a basis for comparing the improvements obtained in RS when including the different context types.

Table 9: The effect of incorporating context into the RS that were evaluated quantitatively

Appr.	Types of context	Application domains	Usage Prediction				Rating Prediction		Ranking Prediction
			Precision	Recall	F-Measure	MAP	MAE	RMSE	
[67]	Human(mood), Time	e-learning	2%	2%	5%				
[50]	Time, Location	Movies		22%			32%		

Table 9: The effect of incorporating context into the RS that were evaluated quantitatively

Appr.	Types of context	Application domains	Usage Prediction				Rating Prediction		Ranking Prediction NDCG, Hit Ratio, MRR
			Precision	Recall	F-Measure	MAP	MAE	RMSE	
[90]	Human (age, gender)	Movies						3%	
[99]	Social, Time	Hotels and Tourism							
[79]	Human (hunger level), Time, Location	Food				15%	9%	9%	
[80]	Social, Time	E-retailing, Movies	6%				17%	14%	
[47]	Location, Time	Point of interest	Between 1,7% and 3,1%				9%	4%	
[51]	Time, Location, Social	Movies	10%						
[72]	Time, Location, Natural (weather), Social	Movies, Hotels and Tourism	Between 80% and 200%; and between 16% and 103%						
[29]	Time, Social, Location	Movies			About 10%				
[98]	Time, Location, Social	Movie	Between 2% and 42%				Between 2% and 6%		
[43]	Time, Location	Music, Point of interest	Between 5% and 33%	Between 5% and 33%	Between 5% and 33%				
[75]	Time	Movies		Between 30% and 35%					
[73]	Human(age, gender), Time, Social	Movies					Between 5% and 30%		
[84]	Social	Not Identified	Between 12% and 22%		About 21%			About 24%	
[76]	Location, Activity	e-retailing	About 53%			About 40%			
[87]	Location, Time, Activity	Point of interest							Hit ratio: About 25%
[68]	Time, Social	General application							Hit ratio: Between 34.56% and 35.91%
[93]	Social	E-commerce					About 10%	About 10%	

Table 9: The effect of incorporating context into the RS that were evaluated quantitatively

Appr.	Types of context	Application domains	Usage Prediction				Rating Prediction		Ranking Prediction NDCG, Hit Ratio, MRR
			Precision	Recall	F-Measure	MAP	MAE	RMSE	
[91]	Social	Books, Music, Movies					Between 9% and 18%	Between 7% and 17%	
[58]	Social	Books, Music, Movies	Avg: 73.27 times better	Avg: 73.27 times better					
[69]	Time	Movies					About 5%		
[92]	Social	General application					Avg: 21%	Avg: 18%	
[31]	Human (user interest)	Web services							NDCG: 40%
[32]	Social	Multimedia	About 25%						
[100]	Social, Location	Points of interest, Hotels & Tourism					Best case: 22%	Best case: 35%	
[65]	Social, Location	Points of interest, Hotels & Tourism	Best case: 15%	Best case: 10%					
[110]	Social, Location, Time	Social networks & Tourism							NDCG: 60%
[101]	Social	General application					Between 10% and 27%		
[59]	Location	Web services					Between 2% and 3%		
[102]	Time	Web services					Between 5% and 20%		
[104]	Social	E-retailing							MRR: between 8% and 25%
[56]	Social	E-retailing	Best case: 78%						
[57]	Different types of context	General application	Best case: 78%						DCG: Between 2.5% and 5%
[106]	Social, Location	Points of interest					Best case: 12.6%	Best case: 14.5%	
[105]	Social	E-retailing					Best case: 16.24%	Best case: 16.09%	

8. Research opportunities

This section provides CARS researchers with a list of research opportunities, most of them borrowed from the studied articles. From each paper, we identified, categorized, and analyzed the challenges that authors defined as worthy of future work. Each subsection corresponds to one of the nine challenge categories that we identified: *dynamic context management, context gathering, context reasoning, contextual modeling, problems inherent in RS, CARS evaluation, users in the loop, self-adaptation and privacy and ethical considerations*.

8.1. Dynamic Context Management

Traditional CARS assume that context information is immutable over time, even when user situations continuously change. Evidence of this are deal recommendation systems that keep sending offers to the user for events currently happening in her home city, despite she is in a several day business trip that is scheduled in her agenda, and the user's agenda as well as her current location can be easily monitored by modern applications [7]. This static vision of context information causes that RS deliver recommendations that are irrelevant to users, which has negative effects for businesses.

To deal with this dynamic nature of context, CARS must be equipped with runtime mechanisms to identify relevant context and integrate it into the recommendation process dynamically [3, 5]. This implies also to enable RS to manage the life cycle of context information at runtime, for instance, to identify context variables that become relevant or irrelevant, and treat them accordingly. For example, by adapting the recommendation model according to new context variables that may become relevant while the user interacts with the system.

Dynamic context management research in RS includes investigating mechanisms to i) identify context changes that affect the relevance of recommendations; ii) characterize the life cycle and dynamics of context information; and iii) develop situation-aware and self-adaptation mechanisms to enable CARS with the ability to adjust recommendation models at runtime. Among the studied papers, [3, 28, 30, 36, 47, 69, 85] declare dynamic context and its management challenges as a future research area.

The following two categories of research opportunities, context gathering and context reasoning, are completely related to dynamic context management, since they are concrete phases of the context information life cycle [5].

8.2. Context Gathering

Context gathering refers to the process of acquiring context information from the user's environment. When the relevant context is dynamic (e.g., context that changes over time such as the purchase intent of a user), context acquisition requires automatic mechanisms to detect context sources that become available at runtime, and deploy the sensors required to gather this information. Context gathering challenges include: i) the acquisition of context information from non-explicit and non-traditional context sources (e.g., to identify user intents and motivations); and ii) the development of user interfaces that allow the acquisition of relevant context, without requiring user explicit inputting through traditional interfaces. The authors of the following papers highlight the importance of context gathering research [27, 40, 45, 48, 60, 76, 84, 96].

8.3. Context Reasoning

Context reasoning refers to the inference of implicit context facts from raw context [5]. When context is highly dynamic, context management mechanisms must support the addition of reasoning rules dynamically. Context reasoning challenges in RS include: i) inferring context facts from the combination of different context variables; ii) understanding, particularly at runtime, the relationships between context situations and user preferences; and iii) exploiting context available in user profiles effectively. Authors of papers [4, 30, 39, 45, 52, 58, 82, 86, 107, 108] identify context reasoning as a relevant research topic.

8.4. Contextual Modeling

Pre-filtering, contextual modeling and post-filtering are the three existing paradigms to incorporate context into RS. In contextual modeling, context information is directly integrated into the recommendation model, which, in many cases, has been proved to be more effective than pre- and post-filtering approaches. As a result, an important number of researchers investigate how to exploit context information through contextual modeling [4, 24, 30, 41, 43, 51, 56, 68, 73, 79, 81, 86, 91, 105, 106]. Contextual modeling challenges include the development of new techniques and mechanisms to: i) integrate context into traditional recommendation models; ii) improve rating estimation methods by exploiting context; and iii) identify the context variables that must be integrated into the recommendation model.

8.5. Problems inherent in RS

Context information can be also useful to solve specific problems in RS. Such is the case of the cold-start, self-biased recommendations, and sparsity problems. Concerning the cold-start problem, context provides information that allows the characterization of users, even when they are newcomers to the system [38, 39, 93, 109]. Regarding the self-biased problem, an important challenge is to develop mechanisms to prevent the self-influence of frequently recommended items on future recommendations; the approach presented by Nocera et al. [66] deals with this problem using a novelty metric that considers social context. Concerning the sparsity problem, context-dependent matrices could help decrease sparsity by taking into account different subsets of dimensions under particular context situations [56, 59, 88, 92, 93, 101, 102, 109]. For example, to infer user ratings in a department store, instead of taking into account all of the products the user has bought in the past, one could use only those products directly associated with the user's current purchase intent (e.g., vacation planning, back to school season).

8.6. CARS evaluation

The evaluation of new methods and techniques is crucial to advance the state of the art of CARS, and to confidently apply new developments in real life. Major evaluation challenges identified from the studied papers are [29, 36, 46, 51, 64, 69, 76, 107]: i) the investigation of new properties and metrics; ii) the development of benchmarks that facilitate the understanding of approaches that perform better in particular circumstances; iii) the development and documentation of real life experiments in different application domains; and iv) the acquisition of contextual real data to improve the quality of validations.

8.7. Users in the loop

There is an increasing tendency to conceive users as part of software systems, instead of entities that simply interact with systems. This is commonly known as *the integration of users in the loop*. Users can be integrated in the recommendation process, at one or several of its phases, for example, through feedback that can be used to improve recommendations. Users in the loop are also valuable sources of relevant context. An important challenge is to achieve a seamless integration to avoid affecting the natural behavior of the user. This challenge category was explicitly addressed in [50].

8.8. Self-adaptation

Self-adaptive software systems adjust their structure or behavior at runtime to control the satisfaction of functional and non-functional requirements [113]. To achieve these dynamic capabilities, these systems are instrumented with feedback loops that measure outputs and compare them against reference inputs. If the measure output does not correspond with the desired value specified in the reference input, a controller adjusts the target system to obtain better results [114]. An interesting research direction for the advancement of recommender systems is to instrument them with feedback loop-based mechanisms that allow them to self-improve at runtime. Authors of paper [33] highlight self-adaptation as a promising research direction. In particular, they are interested in implementing a feedback mechanism that adjusts the semantic similarity metric at runtime with the goal of improving performance.

8.9. Privacy and ethical considerations

Privacy and ethics are important aspects to be considered in CARS. Several relevant challenges arise from the need to assure these aspects, which is particularly difficult at runtime. For example, whenever a new context source is identified as relevant, how to validate with the user that this information can be used by the system, that this usage is transparent to the user, and that this information will be used only for the purposes approved by the user. Privacy and ethical aspects are of paramount importance to develop confidence and trust in the use of personalization in CARS [27].

9. Conclusions

This paper presented a comprehensive characterization of context-aware recommendation processes and systems, based on the findings of a systematic literature review (SLR) we conducted to survey CARS that were published between 2004 and 2016. This study was conducted with the goal of helping practitioners and researchers understand how context information can be effectively combined with recommendation mechanisms. The main results provide a clear understanding about where context information is usually integrated into the recommendation process, the techniques available to exploit context information depending on the underlying recommendation approach and the phase of the process where context is included, the context types more frequently exploited in the different application domains, and the most

common used evaluation mechanisms, including properties, metrics and protocols.

Despite the comprehensiveness of this study, it is unfeasible to conclude about the effectiveness of using particular context types in specific application domains. This is in part because the effect of including context into RS is difficult to generalize given that the results depend on the nature of the used data sets and recommendation approaches. Furthermore, validation methods must be improved to include quantitative measures that allow a more objective evaluation of the proposed approaches—36 out of the 87 studied papers evaluate their systems quantitatively by comparing, against other approaches used as baselines, the improvements obtained with the integration of context information into the recommender system.

Besides the need for improving validation methods, this survey exposes also several research challenges that deserve further investigation. In particular, those related to the need for i) instrumenting CARS with runtime mechanisms to manage context dynamically along its life cycle; ii) developing new techniques to exploit context directly into the recommendation model; iii) exploiting context to solve inherent RS problems, in particular, the cold-start, self-biased recommendations, and sparsity problems; iv) instrumenting RS with self-adaptation capabilities, and v) solving user-oriented issues such as their better integration in the recommendation loop, as well as the privacy and ethical considerations that arise.

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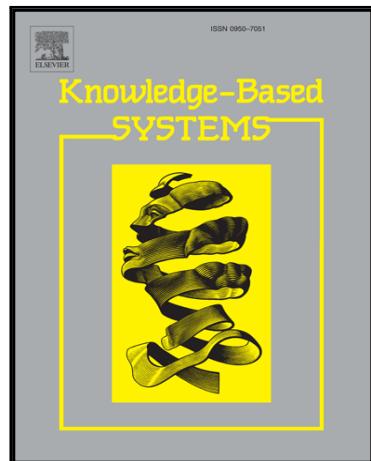
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Characterizing Context-Aware Recommender Systems: A Systematic Literature Review

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Abstract

Context-aware recommender systems leverage the value of recommendations by exploiting context information that affects user preferences and situations, with the goal of recommending items that are really relevant to changing user needs. Despite the importance of context-awareness in the recommender systems realm, researchers and practitioners lack guides that help them understand the state of the art and how to exploit context information to smarten up recommender systems. This paper presents the results of a comprehensive systematic literature review we conducted to survey context-aware recommenders and their mechanisms to exploit context information. The main contribution of this paper is a framework that characterizes context-aware recommendation processes in terms of: i) the recommendation techniques used at every stage of the process, ii) the techniques used to incorporate context, and iii) the stages of the process where context is integrated into the system. This systematic literature review provides a clear understanding about the integration of context into recommender systems, including context types more frequently used in the different application domains and validation mechanisms—explained in terms of the used datasets, properties, metrics, and evaluation protocols. The paper concludes with a set of research opportunities in this field.

Keywords: Recommender systems, Context-aware recommender systems, Pre-filtering, Post-filtering, Context modeling, Recommender systems evaluation

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1. Introduction

With the proliferation of big data & data analytics technologies, recommender systems (RS) are now crucial in seeking customer satisfaction through personalization [1]. RS aim at selecting and proposing the most relevant items, services and offers for their users, by considering their profiles, purchase history, preferences, opinions, interactions with offered products and services, as well as their relationships with other clients. At the same time, the generalization of smart-phones and ubiquitous computing has given RS access to context information [2]. Context-aware recommender systems (CARS) go one step further from traditional RS by exploiting context information such as time, location, and user activity to understand user situations and their influence on user preferences. The incorporation of context information into RS [2, 3] leverages the value of these systems by improving the relevance of possible recommendations with respect to changing user needs [4, 5].

The value of context information to improve the quality of recommendations has been demonstrated and supported by different researchers [6, 7, 8, 9, 10, 11]. Nevertheless, RS as well as context-awareness researchers and practitioners interested in combining the two areas still lack a guide that helps them understand how to exploit context information to smarten up RS. Evidence of this is the absence of comprehensive and domain-independent surveys, particularly systematic literature reviews, that not only consolidate the state of the art of the field, but also explain the most common techniques used to integrate context into the recommendation process. After a rigorous revision of the state of the art, we found that none of the available surveys comprehensively characterize recommendation processes from the perspective of the exploitation of context information. In the best cases, existing surveys focus only on the identification of used context types, and most of them address the problem from the perspective of a particular domain.

This paper presents the findings of a systematic literature review (SLR) [12] on CARS that we conducted with the goal of helping practitioners and researchers understand how context information can be effectively combined with recommendation mechanisms. To this end, we studied a final set of 87 CARS papers that were classified as content-based, collaborative filtering and hybrid approaches. For each paper, we identified recommendation

techniques, means to exploit context information, context types, application domains, validation mechanisms including the used datasets, the improvements obtained through the exploitation of context (when measured quantitatively), and research opportunities. The main results of our study are reported in this paper in the form of a framework that characterizes recommendation processes in terms of: i) the recommendation techniques used at every stage of the process, ii) the techniques used to incorporate context, and iii) the stages of the process where context is integrated into the system. This manuscript aims at providing a clear understanding about where context information is usually integrated into the system, what techniques are available to exploit context information depending on the underlying recommendation approach and the phase of the process where context is included, what context types are more frequently exploited in the different application domains, and what validation mechanisms—explained in terms of the used datasets, properties, metrics and evaluation protocols—are generally used to evaluate the proposed approaches. Last, but not least, the paper discusses research opportunities relevant to CARS.

This paper is structured as follows. Sect. 2 explains foundational concepts on recommender systems and context information. Sect. 3 visits related work by analysing the contributions of our SLR with respect to other surveys published on CARS. Sect. 4 explains the methodology we followed to conduct the SLR. Sects. 5–8 constitute the contributions of this manuscript: Sect. 5 presents the findings of our SLR and the characterization framework for CARS; Sect. 6 reports on the validation methods and datasets identified in the studied approaches; Sect. 7 presents quantitative data, reported in the studied papers, on the improvements obtained from the exploitation of context information; and Sect. 8 summarizes and classifies research opportunities. Finally, Sect. 9 concludes the paper.

2. Background

This section briefly presents the fundamentals of RS, and context information as an enabler to improve the quality of recommendations.

2.1. Recommender systems (RS)

Dating back to the mid 1990s, the first recommender systems emerged by following two well differentiated paths. On the one hand, *content-based recommenders* drew from the fields of document retrieval [13, 14] and user

profiling [15] to define a common representation space for describing items and users. User profiles result from the aggregation of items that have been favorably or unfavorably qualified in the past. For a given user, items similar to the user's profile are recommended, without taking into account information from other users. On the other hand, *collaborative filtering recommenders* evolved from contributions in human computer interaction [16, 17], where the preferences and choices of similar users are used as the basis for recommendation.

Each of these two types of systems has advantages and disadvantages. Content-based recommenders are easy to explain and understand, prove a good starting point for item navigation, and allow recommendations for new users and/or items (cold start problem). However, they imply the cumbersome task of thoroughly and explicitly describing all items using a common set of features, do not work with implied content, can only handle complementary item recommendation and, being centered on a single user, do not allow the recommendation of serendipitous items. In contrast, collaborative filtering recommenders are based on the common preferences of crowds of users. Thus, these systems cannot only recommend complementary as well as substitute items, but also surprise users by recommending unusual items. Nevertheless, they are not as transparent on their recommendations, need substantially more user data to work well, and do not provide a way to deal with the cold start problem.

Hybrid recommenders, a third type of RS, provide a middle ground between content-based and collaborative filtering systems, by leveraging their strengths and mitigating their drawbacks.

This categorization of RS was proposed by Adomavicius and Tuzhilin in [6]. Other authors have proposed other types of systems [1, 18]. In particular, we consider case-based and knowledge-based systems to be subtypes of the content-based family, community-based systems to be subtypes of the collaborative filtering family, and demographic recommenders to be either content-based or collaborative filtering systems following a pre-filtering stage where data are partitioned in subsets according to user characteristics.

RS use information from items, users, and preferences. The main source of information is the item by user matrix that stores user preferences for individual items. These preferences can be explicitly stated (e.g., in the form of ratings or likes), or implicitly inferred from the interactions of the user with the system (e.g., purchases, accesses or reads). Content-based recommenders consider additional sources of information in the form of feature vectors de-

scribing different characteristics of each item (e.g., category, size, age, brand, author).

The characterization of CARS presented in this paper is driven by the stages of the processes followed by content-based and collaborative filtering systems.

2.2. Context information

Abowd et al. define *context* as “*any information useful to characterize the situation of an entity (e.g., a user or an item) that can affect the way users interact with systems*”[2]. The precision of recommendations may result highly affected by context information [7, 8]. For example, a costumer could be more or less interested in a particular restaurant depending on the day of the week. Contextual information can be defined as static or dynamic [3]. When context is static, recommender applications assume that this information is immutable over time. An example of static context is the birthday of a user. On the contrary, dynamic context changes over time thus highly affecting user current needs. Instances of dynamic context are location, time, and user activity [5].

2.2.1. Context categories

Villegas et al. [5] characterize context along five general categories: individual, location, time, activity, and relational. Other characterizations, which can be instantiated from these general categories, have been proposed for domain specific CARS (e.g., the one proposed by Verbert et al. in [19] for CARS in the learning realm). To identify the context types exploited by the CARS studied in this SLR, we based on the classification of context information proposed by Villegas et al., which is summarized as follows:

- **Individual context:** Corresponds to information observed from independent entities (e.g., users or items) that may share common features. This category can be sub-classified into *natural*, *human*, *artificial*, or *groups of entities*. *Natural context* represents characteristics of living and non-living entities that occur naturally, that is, without human intervention (e.g. weather information). *Human context* describes user behavior and preferences (e.g., user payment preferences). *Artificial context* describes entities that result from human actions or technical processes (e.g., hardware and software configurations used in e-commerce platforms). The last subcategory, *groups of entities*, concerns groups of independent subjects that

share common features, and that might relate each other (e.g., preferences of users in the user's social network).

- **Location context:** Refers to the place associated with an entity's activity (e.g., the city where a user lives). This category is sub-classified as *physical* (e.g., the coordinates of the user's location, a movie theater's address, or the directions to reach the movie theater from the costumer's current location), and *virtual* (e.g., the IP address of a computer that is located within a network).
- **Time context:** Corresponds to information such as time of the day, current time, day of the week, and season of the year. Time context can be categorized as *definite* and *indefinite*. *Definite* context indicates time frames with specific begin and end points. *Indefinite* context refers to recurrent events that occur while another situation takes place, so it does not have a defined duration (e.g. a user's session in an e-commerce application).
- **Activity context:** Refers to the tasks performed by entities (e.g., shopping, the task a user does at a particular time).
- **Relational context:** Refers to entity relationships that arise from the circumstances in which the entities are involved [20]. Relational context can be defined as *social* (i.e., interpersonal relations such as associations or affiliations), *functional* (i.e. the usage than an entity makes of another).

2.2.2. Integrating Context into Recommender Systems

Traditional recommender systems rely on information about users and items. In contrast, CARS rely also on context information that is relevant for the recommendation. Therefore, recommendation tasks in context-aware recommender systems can be seen as a function of users, items and context information [8]:

$$f : \text{Users} \times \text{Items} \times \text{Context} \rightarrow R \quad (1)$$

There exists three paradigms to integrate context information into recommender systems, depending on the phase of the recommendation process at which context is processed [8]:

- **Contextual pre-filtering:** Context information is used as a filtering mechanism applied to the data, before the application of the recommendation model.

- **Contextual post-filtering:** Context information is initially ignored, and preferences are computed by applying traditional recommender algorithms on the entire data. The resulting set of recommendations is then filtered according to context information that is relevant to the user.
- **Contextual modeling:** Context information is directly integrated into the recommendation model, for example as part of the preference computation process.

This SLR characterizes CARS by considering these three paradigms to incorporate context into the recommendation process, and the techniques used for this integration.

3. Related work

We found 15 RS surveys published in relevant venues and journals between 2004 and 2016. However, only 7 out of these 15 surveys, published between 2012 and 2014, relate to the improvement of RS through the incorporation of context information. Aiming at providing a comprehensive understanding of the state of the art of this field, our SLR not only follows a well defined research methodology, but also characterizes CARS along all application domains, context types, and techniques reported in the studied literature. Most importantly, we documented the recommendation processes followed by content-based and collaborative filtering CARS, to characterize how these systems exploit context information along all phases of the process. The characterization includes recommendation techniques, paradigms for incorporating context, context types, application domains, and a detailed explanation of the mechanisms used to exploit context. We also compiled a catalog of datasets and validation methods used in the studied approaches, as well as a list of open challenges.

Table 1 compares our literature review (last row) with the most relevant CARS surveys we found in the state of the art. This comparison is based on seven criteria that we define as follows: *i) SLR*, the literature review follows a systematic methodology; *ii) not focused on particular domains or techniques*, the survey reviews the state of the art across all identified domains and techniques; *iii) not focused on particular context types*, the survey reports the exploitation of different context types; *iv) identifies context exploitation techniques*, the survey reports the ways how context was exploited

in the studied RS; *v)* *context in the stages of the recommendation process*, the literature review documents how context is exploited along the stages of the recommendation process; *vi)* *datasets*, the survey lists the datasets used by the studied systems; and *vii)* *validation techniques*, the review reports the techniques used to evaluate the studied approaches. The plus sign in a cell indicates that the survey is compliant with the corresponding criterion, whereas the absence of the sign indicates that it is not.

Table 1: Related work—Comparing our SLR with other surveys on CARS

Author/Year	SLR	Not focused on particular domains or techniques	Not focused on particular context types	Identifies context exploitation techniques	Context in the stages of the recommendation process	Datasets	Validation techniques
Verbert et al., 2012 [19]			+	+			+
Kaminskas and Ricci, 2012 [21]			+	+			+
Liu et al., 2013 [22]			+				
Champiri et al., 2014 [23]			+	+			
Campos et al., 2014 [24]		+					+
Inzunza et al., 2016 [25]	+	+	+				
Seifu and Mogalla., 2016 [26]		+	+				
Our literature review	+	+	+	+	+	+	+

According to Table 1, four surveys focus on particular domains: learning processes [19], music services [21], digital libraries [23], and mobile applications [22]. All surveys identify the different types of context exploited in the studied RS, except the one by Campos et al. [24] that focuses on time context only. Furthermore, this survey does not provide insights on the exploitation of context into RS (context exploitation techniques are not identified), but on the evaluation methods used to evaluate the effectiveness of CARS. The surveys conducted by Verbert et al. [19], and Kaminskas and Ricci [21] describe the techniques used to exploit context in the studied systems and the means used to validate them. However, they focus on particular domains. The survey by Liu et al. [22] focuses only on methods to identify the relevant context and the context types exploited in mobile systems. Thus, besides being do-

main specific, it does not report on techniques used to take advantage of context. As our literature review, the survey conducted by Inzuza et al. [25] follows a systematic approach and does not relate to a particular application domain, technique or context type. However, it does not report on context exploitation techniques. Also similarly to our work, the work conducted by Seifu and Mogalla [26] aims at characterizing the process followed by CARS in the form of what they call “*a framework of CARS*.” Nevertheless, their focus is not the way how context is incorporated and exploited, and the explanation of the framework in their six page paper is not as comprehensive as our characterization. Finally, none of the studied surveys report on the used datasets or relate context and its means to exploit it to the concrete phases of the recommendation process.

4. Methodological aspects

We conducted this study by following the guidelines proposed by Kitchenham and Charters in [12]. With our long-term research goal in mind—*to look for innovative and more effective ways of exploiting context information to improve the effectiveness of recommender systems*, we defined the set of research questions that would allow us to understand the state of the art of CARS. These questions are stated as follows:

- RQ1: How is context information exploited along the recommendation process?
- RQ2: What are the existing techniques used to incorporate context information into RS? For each technique, what are the most common application domains?
- RQ3: Is there any correlation between techniques used to incorporate context into RS and any of the traditional recommendation approaches (i.e., content-based, collaborative filtering and hybrid)?
- RQ4: What are the types of context more commonly exploited by RS? What techniques apply in each case?
- RQ5: What evaluation methods have been used to validate the effectiveness of CARS? What are the most common metrics used by these methods?

To answer these research questions and understand the way how context information is integrated into recommender systems, it was important first to characterize the processes that are followed by these systems, in particular by content-based and collaborative filtering approaches. That is, to understand the data that constitute the inputs, and the stages implemented by each type of recommender system to generate recommendations. This process-oriented characterization allowed us not only to report the techniques and context used by the studied RS, but also to map them to specific phases of the recommendation process, with the goal of leveraging the usefulness of this SLR for understanding the state of the art of this field.

We conducted a bibliographic search of conference proceedings and journal papers published in IEEE, ACM, ScienceDirect, EBSCO and Springer. These databases were selected because of the quality of their publications, and their relevance to RS. We used the search string (*("recommendation systems" OR "recommender systems" OR "recommendation" OR "recommendations") AND ("context aware" OR "context-aware" OR "context information" OR "contextual information" OR "location" OR "social" OR "time" OR "activity" OR "task" OR "environmental")*).

To select the papers to be included in the study we applied four filters: i) *publication date*, we selected papers published between 2004 and 2016; ii) *publication type, number of citations and language*, we excluded workshop and symposium proceedings, papers with less than 10 citations (with some exceptions for papers recently published) and non-English papers; iii) *relevance*, we studied the abstracts to verify the relevance of each paper. After this third filter, we obtained a total of 286 articles, including surveys on RS.

We thoroughly analyzed all these 286 articles and characterized those proposing CARS according to seven criteria: i) *recommendation system approach*, whether it is content-based, collaborative filtering, or hybrid; ii) *recommendation techniques*, the mechanisms used at the different stages of the recommendation process; iii) *paradigm for incorporating context*, whether it is pre-filtering, post-filtering, or contextual modeling; iv) *context types*, the context categories that are exploited in the recommender system (based on the classification proposed by Villegas and Müller [5]); v) *application domain* (if applicable), the specific area targeted by the proposed RS; vi) *evaluation*, the methods and metrics used to validate the effectiveness of the proposed RS; and vii) *data sets* (when reported), the data used to evaluate the proposed approach.

The fourth and last filter consisted in excluding those papers for which we could not identify any of the mandatory criteria presented above. The final set of papers includes 87 manuscripts that propose CARS and 15 surveys, including four highly relevant papers that were published in 2017.

5. Characterization of Context-Aware RS (CARS)

This section summarizes, for each type of recommender system, the findings of our SLR. We consider that the differences between content-based, collaborative filtering, and hybrid recommenders are too profound to analyze them all together, thus we set to do it independently.

To characterize content-based and collaborative filtering CARS, we first represented their recommendation processes using flow diagrams (cf. Figs. 1 and 2) that allow us to distinguish the different phases they comprise, and identify the points where context information is exploited by the surveyed RS, following either the pre-filtering, post-filtering or contextual modeling paradigms.

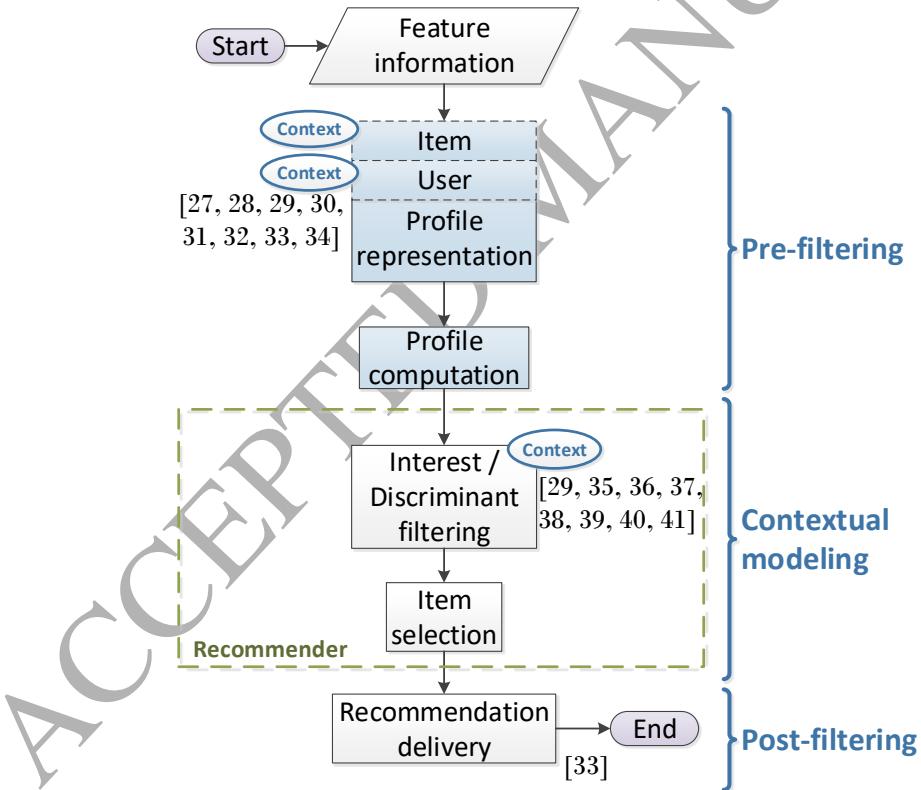
Bold ovals labeled as “Context” indicate the points of the process where we consider that context information can be incorporated. Citations next to each oval correspond to the studied approaches that integrate context in that specific phase of the recommendation process. The absence of citations next to an oval indicates that although we consider context can be exploited at that phase of the process, we found no approaches that do so. Furthermore, each brace depicted in the diagrams groups the stages of the process associated with each of the three paradigms commonly used to incorporate context into a CARS (i.e., pre-filtering, contextual modeling and post-filtering).

It is important to stress out that we focus on the ways in which context can be incorporated and exploited in the recommendation process. Even though on the diagrams we illustrate that process as a whole, we are mainly interested in showing the specific points where the reviewed papers (their references are placed accordingly on the diagrams) decided to adapt the recommendation process to exploit context. While we rely on some of the reviewed papers to illustrate the characterization and findings presented in this section, a more detailed retelling on how each paper implements their system and incorporates context can be found on Tables 2 and 3.

5.1. Content-based approaches

We found 15 papers associated with content-based CARS. Table 2 summarizes the characterization of these papers (cf. Column *Appr.*), which is driven by the process depicted in Fig. 1. Columns *Profile representation*, *Profile computation*, and *Discr. filter* indicate the techniques implemented by the studied systems to realize the main phases of the content-based recommendation process. Column *Paradigm* denotes the strategy used to incorporate context information: pre-filtering, contextual modeling, post-filtering. Column *Context Types* corresponds to the context categories exploited by the corresponding approach. Column *Domains* lists the application domains for which the RS was proposed. The last column explains the means used by the studied CARS to exploit context information.

Figure 1: Process followed by content-based CARS



5.1.1. The beginning of the process

The process implemented by content-based CARS (cf. Fig. 1) begins with the identification of the features in the available data that will define the common dimensional space used to describe item characteristics and user preferences (cf. *User profile definition* and *Item profile definition* in Fig. 1).

Pre-filtering strategies are applicable through the incorporation of contextual factors in the definition of item and/or user profiles. These strategies reduce significantly the search space for the discriminant filter by initially discarding a part of the information available. However, they require the inclusion of redundant user or item profiles for different contextual situations.

All content-based reviewed papers defined the features used as the basis for their recommendation, but only about half of them included contextual information as features. CARS proposed in [27, 28, 29, 30, 31, 32, 33, 34] exploit context using a pre-filtering strategy to generate different contextual *user* profiles for the same user, with different preferences for different situations (see Table 2 for more details regarding the four papers that apply pre-filtering as the paradigm to incorporate context). For instance, [29] proposes a movie CARS where contextual variables of different types such as time (weekday, weekend), location (theater, home), and social context (companion, friends, family) are taken into account to consider or ignore past user ratings, by building several context-aware (micro) profiles that are used to generate context-aware recommendations. As a result, the same user can have different profiles.

None of the surveyed papers associate contextual information with items. We assume that this is because it is easier to think in terms of contextual user profiles than in terms of contextual item profiles, probably because user preferences naturally vary according to context situations. Still, it is completely possible to have different *item* profiles for different situations. Nevertheless, since very often the number of items is many times larger than the number of users, it would mean increasing the complexity of the recommendation process given that a considerably larger number of items must be handled by the system.

5.1.2. The core of the process

The next phase is the core of the recommendation process. In general, a discriminant filter working as a utility function between user and item profiles is responsible for generating a recommendation score from the item and user vectors. This can be done through several strategies: i) by applying

some similarity measure such as *Cosine Similarity* (since items and users are represented on the same dimensional feature space, it is possible to compute the distances or similarities between them, with the goal of selecting the items closer to the user's preferences [27, 28, 29, 30, 31, 34, 35, 36]); ii) by obtaining a given classification score by applying a supervised learning technique ([37, 38, 39]); or iii) by applying a heuristic approach (context information can be considered into a discriminant filter, not as additional profile dimensions, but as an integral part of the function definition [32, 33, 35, 40, 41]). Either way, the recommender engine will associate a numeric value to each item, order the items accordingly, and select the ones that appear at the top or that surpass a specified threshold.

At this stage of the process, contextual information can be incorporated by influencing the similarity or distance between items and users. For example, [36] proposes a music recommendation system that incorporates the time at which users accessed different items (songs) in order to provide more relevant recommendations. In their system, users are described by a vector of their correlations to the considered time-related contexts (dawn, morning, monday, tuesday, spring, christmas), items are described as a vector of their correlations to the domain features (e.g., band, genre) as computed by a TF-IDF measure, and the historical accesses to items by users are kept as a collection of pairs of vectors as previously described. To perform a recommendation, the cosine similarity measure is applied to the user's current context and the historical accesses, the similarity of the historical accesses to the items is computed, and an aggregation of both measures allows the scoring of every available songs, so that the top five songs are presented to the user.

5.1.3. The end of the process

Finally, the selected recommendations are organized and delivered to the user. Post-filtering strategies apply at this stage to eliminate the recommendations that are irrelevant to the user's current context. We found that only the RS presented in [33] applied this paradigm to filter out movie recommendations that did not correspond to the current time and location.

5.1.4. Findings

Regarding the paradigm used to incorporate context into the RS (cf. Sect. 2.2.2), findings show that content-based approaches use contextual modeling as much as pre-filtering (one of those combining both strategies);

both paradigms being followed by 53% of the papers. Only one of the studied content-based CARS [33] incorporates context information using post-filtering, combined with pre-filtering. We hypothesize that this may be in part because post-filtering strategies may result in wasting time and computational resources, since the obtained recommendations may become useless after evaluating them with respect to the current context of the user, which is taken into account only at the end of the process. Indeed, pre-filtering approaches provide more benefits in what respects to computational complexity, and contextual-modeling solutions have proven to be more effective for the accuracy of recommendations [4].

With respect to the types of contextual information commonly used in the reviewed systems, and their application domains, we found that time context is commonly used in application domains such as movies and news; location context, in domains associated with movies, music and points of interest; activity context in domains related to movies, music and points of interest; social context in multimedia applications and human context in web services recommendations. It is of particular interest that none of the reviewed content-based CARS target the e-retailing domain, an otherwise popular application domain in traditional RS.

Table 2: Characterization of content-based approaches

Appr.	Profile representation	Profile computation	Discr. filter	Paradigm	Context types	Domains	Means to incorporate context
[28]	Item features	Case based reasoning (CBR)	Cosine similarity	Pre-filtering	Time, Location, Activity, Artificial (environment)	Movies, Music, News	Generates a contextual user profile by revising the user's consumption behavior. Then, it uses cosine correlation to measure the similarity between the user contextual profile and the item profile.
[37]	Item features	Heuristic approach	Decision tree algorithm	Cont. Model.	Activity, Human (age, gender)	Indoor Shopping, Points of interest	Proposes a framework where the relationship between user profiles and services under the same context situation are analyzed to infer user preference rules, using the decision tree algorithm.
[27]	Item features structured by a reference ontology	Heuristic approach	Cosine similarity	Pre-filtering	Activity, Time, Location	Movies	Tracks user browsing behavior, and understands user preferences in each particular context. Then, it performs recommendations by means of an aggregation agent that selects the top N items with the highest inferred values.

Table 2: Characterization of content-based approaches

Appr.	Profile representation	Profile computation	Discr. filter	Paradigm	Context types	Domains	Means to incorporate context
[30]	Tag-based features	Heuristic approach	Cosine similarity	Pre-filtering	Time, Location, Activity, Natural (Weather)	Points of interest	Uses a relational Markov network to match the features of Points of Interest (POI) with the current context. POI's features (e.g. outdoor seating, waiter service, dinner) are taken as the inputs to a neural network used to classify the appropriate level of interest (5 categories) of the user for the POI, under the given context situation. The resulting vector that characterizes the POI is then compared to the user vector using cosine similarity.
[29]	Item features	Heuristic approach	Cosine similarity	Pre-filtering, Cont. Model.	Time, Social, Location	Movies	Pre-filtering: Splits user ratings according to the contextual situation in which the preference is expressed, then builds several context-aware (micro) profiles used to infer preferences for new products. Contextual Modeling: Considers context as a weighting factor that influences the recommendation score of a user for a certain item. It combines the non-contextual vector space representation of user preferences with a vector space representation of context, which is built using the pre-filtering approach.
[35]	Latent semantic features	Term frequency inverse document frequency (TF-IDF)	Cosine similarity	Cont. Model.	Location	News	User is defined by the articles read in the past along with his/her location. The system seeks to rank a set of articles that satisfy the geographical location of the user. The preference score is determined by a cosine function ($f(a, l)$) that measures the appropriateness of each article a to a location l .
[38]	Item features	Heuristic approach	Joint probabilistic distribution	Cont. Model.	Activity	Music	Formulates the context-aware recommendation of songs as a two-step process: i) infers the user's current situation category given some contextual features sensed from a mobile phone, and ii) finds a song that matches the given situation. The first part computes a probability distribution using the Bayes' rule. The second part computes a prior probability that captures the history of user preferences.
[40]	Item features	Heuristic approach	Heuristic approach	Cont. Model.	Location	Indoor shopping	Focuses on mobile recommender systems for assisting indoor shopping by considering location-context. User preferences are calculated through a heuristic approach that integrates three factors: i) time spent in a brand store, ii) frequency of visits to the store, and iii) the matching between the special offers or promotional activities done in the brand store and the user's preferences.
[36]	Item features	Term frequency inverse document frequency (TF-IDF)	Cosine similarity	Cont. Model.	Time	Music	Context refers to the time at which the user listens to a song. The approach predicts user preferences by: i) computing the similarity between the user's current and historical contexts, ii) computing the correlation between historical context and an item, and iii) deriving the expected preference by multiplying measures obtained in i) and ii).

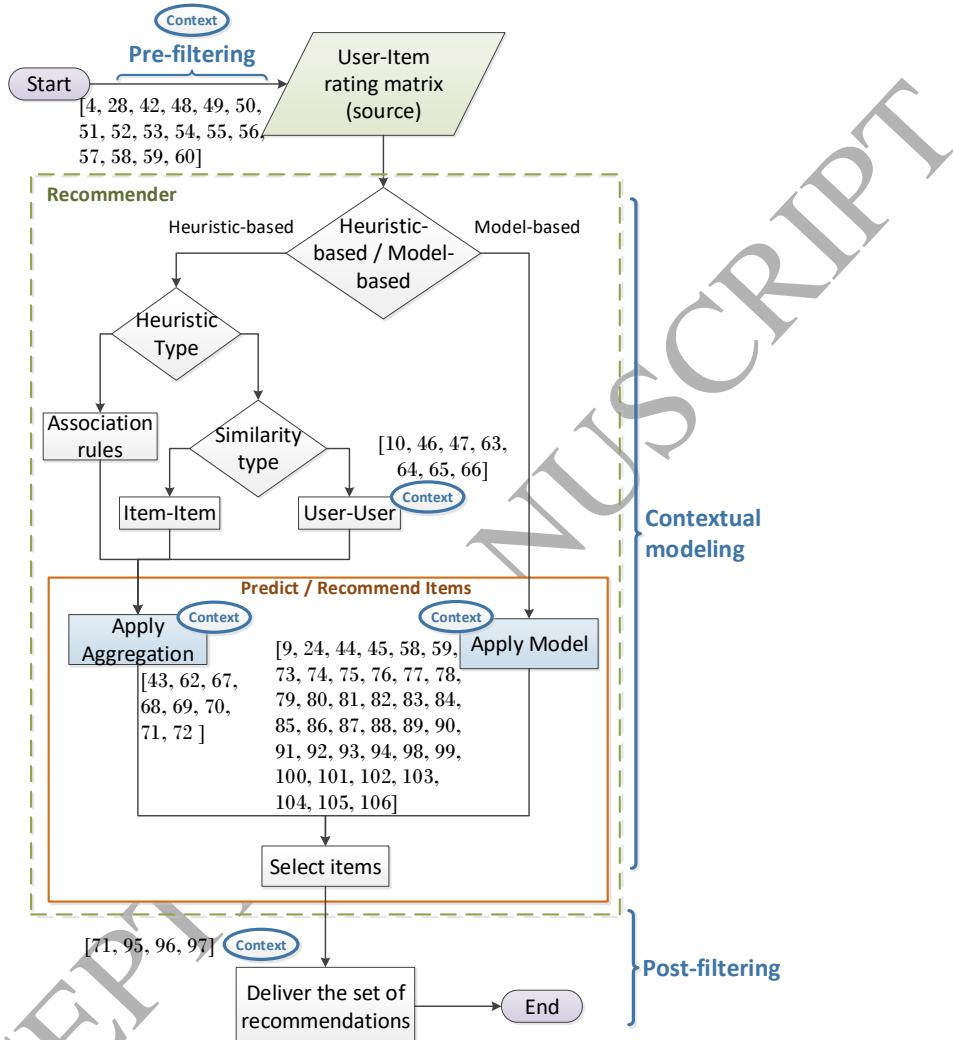
Table 2: Characterization of content-based approaches

Appr.	Profile representation	Profile computation	Discr. filter	Paradigm	Context types	Domains	Means to incorporate context
[39]	Latent semantic features	Heuristic approach	Joint probabilistic distribution	Cont. Model.	Activity, Location	Music	Implements a recommendation model where a set of latent topics is used to associate music content with a user's music preferences under certain location. It is based on the joint probability distribution of user, place, song and lyrics. The latent topics are the intrinsic factors that explain why users prefer certain pieces of music in a particular location and during a specific time period.
[31]	Item features	TF-IDF	Cosine similarity, Jaccard similarity	Pre-filtering	Human (user-interest)	Web services	Infers user preferences from the description of the web services that have been accessed by the user.
[32]	Item features	Heuristic	Heuristic	Pre-filtering	Social (followers)	Multimedia	Utilizes Social context (followers) as the basis to decide on user-similarity.
[41]	Item features	Heuristic	Heuristic	Contextual modeling	Location	Points of Interest	Considers context as a weighting factor that influences the recommendation score of a user for a certain item.
[33]	Item property	Heuristic	Heuristic	Pre-Filt, Post-Filt.	Location, Time	Movies	Recommends items with a composite structure (movie theater + movie + showtime). This approach first computes a similarity metric that concerns to the relation between the composite item (theater, movie, showtime) -Pre-Filtering. Then, this similarity measure is incorporated into the discriminant filter -Post-Filtering.
[34]	Item feature	Heuristic	Euclidian Distance	Pre-filtering	Activity	General application	Utilizes a sequential patterns method to find rules from data records on users' smart-phones. Then, by detecting and matching the user's current situation to the rules, which consider his current context and the events in which he has participated, the system determines the most suitable rules for making just-in-time recommendations.

5.2. Collaborative filtering approaches

Figure 2 depicts the general process followed by collaborative filtering CARS. Based on this process, we characterized the 69 collaborative filtering CARS studied in our SLR. This characterization is summarized in Table 3. Column *Recommendation strategy* presents the techniques implemented by the studied approaches, which can follow different paths of the recommendation process, as explained later in this section. As in the characterization of content-based CARS (cf. Table 2), the characterization of collaborative filtering CARS includes the paradigm used to incorporate context into the system (cf. column *Paradigm*), the types of context information exploited by the studied approaches (cf. column *Context Types*), the application domain (cf. column *Domains*) and the mechanisms used to exploit context (cf. column *Means to incorporate context*).

Figure 2: Process followed by collaborative filtering CARS



5.2.1. The beginning of the process

The input of the collaborative filtering process is a user-item rating matrix, where usually rows represent users, and columns represent items. This matrix can include additional dimensions to represent contextual information in the form of synthetic columns or rows, as in the case of the systems presented in [4, 42, 43, 44]. For example, Baltrunas et al. [42] extend the

user-item rating matrix into a user-item-context matrix, where contextual information consists in categorical tags (e.g. sunny, cloudy, raining) associated with a given rating.

Depending on the application domain, this matrix can be either obtained directly from the interactions of users with items (e.g., by capturing media accesses instantly [28, 45, 46, 47]), or inferred from historical interactions stored in transactional databases (e.g., by analyzing event logs of previous accesses to the recommended items [10, 48]). This matrix can be very sparse and its processing can be computationally challenging when the number of users and items is considerable (several hundreds of thousands).

At the beginning of the process, *pre-filtering* strategies generate different contextual user-item rating matrices, independent of each other. On the one hand, pre-filtering strategies reduce computational complexity since only a portion of the rating matrix is considered; on the other hand, they imply an extra effort in the acquisition of information, since ratings must be generated for every contextual situation that remains relevant after applying the filter.

We identified 16 papers reporting on the application of context-based pre-filtering strategies to generate recommendations [4, 28, 42, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60]. Pre-filtering is a simple strategy that discards a large part of the data to be analyzed, according to the user's current context. An instance is the process followed by the CARS proposed by Lee et al. [48], in which the authors analyze the access logs to songs, and extract context from the timestamps. Then, they define fuzzy membership functions to fuzzy sets for different contextual variables such as season, time of day, or day of the week, in such a way that the same song recommended at different moments is not considered to be the same item. Another example of collaborative-filtering pre-filtering CARS is the one proposed by Baltrunas et al. [42]: if a statistical test shows that context affects the consumption of an item, they split the item into several synthetic items according to the context situation. For instance, a movie could be split into the same movie associated with winter time, and another one associated with summer time.

5.2.2. The core of the process

To perform the actual recommendation, we identified that most systems apply one of two types of collaborative filtering approaches: *heuristic-based* and *model-based* methods. We found no relationships between any of these methods and particular application domains.

Heuristic-based methods. In the studied systems, heuristic-based approaches are realized through association rules, or the analysis of similarities between users or items. The Apriori algorithm [61] is a common technique for association rule learning. First, it identifies the frequent individual items in the database. Then, it extends them to larger itemsets as long as those appear often enough in the database. Finally, these itemsets are used to determine association rules that allow the discovery of hidden relationships in the data, based on the conditional probability existing between itemsets. The association rules approach is mainly applied to transactional data. However, it can also be applied to the user-item rating matrix, by considering each user row as a single transaction.

An interesting finding of our SLR is that despite approaches such as the one reported in [62] mine association rules, none of the studied systems exploit this technique to incorporate context. A reason for this could be that it would imply extra efforts to acquire the information required to generate a more comprehensive rating matrix, such that the extracted rules are meaningful enough in terms of support, and include context in rule antecedents.

Heuristic-based approaches based on similarity analysis consist in determining the distance between users or items. Each user can be seen as a vector in a feature space with an independent dimension associated with each item (and vice-versa). In general, these distances are determined using neighbourhood or clustering-based methods.

These methods work in two ways. The first one, user-user collaborative filtering, consists in inferring user preferences by determining the group of users that are more similar to the target user, and aggregating the items that are most popular among the members of the user group. The second one, item-item collaborative filtering, consists in determining the similarity among items rated by similar users. In either case, the method requires the computation of the distances between users or items, which can be computationally demanding when dealing with a considerable number of users or items.

Seven of the heuristic-based approaches included in this SLR incorporate context through user-user similarity matching; for instance, the approaches presented in [10, 46, 47, 63, 64, 65, 66] incorporate context to the analysis of user-user similarities (more details can be found on Table 3). On the other hand, none of the heuristic-based approaches use item-item collaborative filtering to incorporate context. As discussed previously, we hypothesize that this is because it results more natural to associate context with users

than with items. Nevertheless, in some application domains (e.g., products that are mainly consumed in a particular time of the day), context can be effectively associated with items, in which case an item-item collaborative filtering method that incorporates context would be an appropriate strategy.

Continuing with the recommendation process based on heuristic methods, the information obtained from applying the selected method is aggregated to rank the items to be recommended. Eight of the reviewed papers correspond to collaborative filtering RS that incorporate context as additional factors in the aggregation function. In particular, by using a maximization function [43, 62], a sum of products [67, 68, 69, 70, 71], and probabilities [72]. For instance, Khalid et al. [62] combine the approximated time required to reach a restaurant, the road speed conditions and the distance from the user into a defined metric. Then, the restaurant maximizing this metric is recommended to the user.

Model-based methods. Model-based approaches rely mostly on latent factor models applied to the user-item rating matrix. As we have said before, we can interpret this matrix as either a multi-dimensional representation space where each user is a vector with each item as a dimension, or a multi-dimensional representation space where each item is a vector with each user as a dimension.

The idea of latent factors RS is to obtain a single multi-dimensional space where both users and items can be represented, side by side, through matrix decomposition techniques. In this latent space (usually of smaller dimensionality than the user-item rating space), it is then possible to compute similarities and distances between users and users, users and items, and items and items.

We identified that some systems introduce contextual factors as additional dimensions of the original matrix (e.g., [44, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83]), while some other include contextual information as additive biases on users and items, to affect the calculation of missing ratings (e.g., [9, 45, 84, 85, 86, 87, 88, 89, 90, 91, 92]). An example of the first group is presented in [73], where the authors perform contextual recommendations using tensor factorization. This technique stores the latent feature of users, items and context types in three different matrices. Then, ratings are calculated as the inner product of the latent feature vectors of the given matrices. As a case of the second group, we can consider the RS presented in [85], which performs context-aware recommendations by incorporating temporal changes into the

matrix factorization technique. In particular, this approach seeks to capture past temporal patterns over products and items to predict future behaviour, and thus infer preferences. A particular case is the approach presented by Liu et al. [93], which incorporates social context from a social network into the recommendation model by considering that users belonging to different social groups should have different hyperparameters to be used during the matrix factorization process.

It is important to note that despite the collaborative filtering recommendation process indicates that heuristic-based and model-based techniques are not commonly used together, the authors of papers [9] and [88] propose CARS where model-based and heuristic-based techniques are combined. For instance, in [9] user interactions are represented in the form of a social network graph, where each node represents a user, and arc weights correspond to the trust existing between users represented by adjacent nodes (i.e., social context). This approach uses a heuristic-based technique (i.e., graph theory) along with a model-based method (i.e., matrix factorization).

We found a few papers reporting on the application of other approaches. In particular, machine learning techniques, where context information is usually incorporated by implementing probabilistic models such as the Bayesian model [24, 94], or the usage of classifiers such as support vector machines [81, 82, 83].

5.2.3. The end of the process

Similarly to content-based CARS, at the end of the process a contextual filter can be applied to the resulting recommendations to eliminate those items that are irrelevant to the current context. We found four papers reporting on the incorporation of context as a post-filtering strategy to ignore [95], filter [72, 96, 97], or adjust [72, 96] the inferred recommendations.

For example, the systems reported in [72, 96] ignore context until a traditional collaborative filtering algorithm produces restaurant recommendations, which are then adjusted to the user's current context.

Table 3: Characterization of collaborative filtering approaches

Appr.	Recommendation strategy	Paradigm	Context types	Domains	Means to incorporate context
[4]	Heuristic-based, User sim: Cosine similarity, Aggr.: Sum of products	Pre-filt.	Time, Social, Location	Movies	Filter information according to the current context. A rating is computed for the given user and item, as an aggregation of the ratings of other similar users.
[48]	Heuristic-based, User sim: Cosine similarity, Aggr.: Sum of products	Pre-filt.		Music	
[49]	Heuristic-based, User sim: Cosine similarity, Aggr.: Top N (most important users)	Pre-filt.		Movies	
[50, 51]	Heuristic-based, User sim: Pearson correlation, Aggr.: Sum of products	Pre-filt.	Time, Location	Movies	Filter information according to the current context. A rating is computed for the given user and item, as an aggregation of the ratings of other similar users.
[52]	Heuristic-based, User sim: Pearson correlation, Aggr.: Sum of products	Pre-filt.	Location	Points of interest	
[28]	Heuristic-based, User sim: Pearson correlation, Aggr.: Sum of products	Pre-filt.	Location, Activity, Artificial (environment)	Movies, Music, News	
[53]	Heuristic-based, User & Item sim: K-medians, Aggr.: Maximum	Pre-filt.	Time	E-retailing	The authors propose a neighbor-based collaborative filtering approach. A similarity measure over human and time contextual factors provides the basis for estimating the neighborhood of both users and items that will be considered in the recommendation process.
	Heuristic-based, User & Item sim: Graph theory, Aggr.: Maximum				
[54]	Heuristic-based, User sim: Graph Theory, Aggr.: Maximum	Pre-filt.	Location, Social	Points of Interest	
[60]	Heuristic-based, User & Item sim: Cosine similarity, Aggr.: Sum of products	Pre-filt.	Time	Movies, Music	The authors propose a neighbor-based collaborative filtering approach. A similarity measure over human and time contextual factors provides the basis for estimating the neighborhood of both users and items that will be considered in the recommendation process.
[42]	Model-based, Tech.: Matrix Fact.	Pre-filt.	Time, Social	Movies	Splits items that have been rated under different context situations. This split is performed only if there is statistical evidence that under these context situations users rate items differently.
[55]	Model-based, Tech.: Markov Chains	Pre-filt.	Time, Activity	General application	Processes user historical logs to extract contextual features such as day, time range, and location. Then, it identifies common preferences under different contextual conditions. Finally, it makes recommendations based on distributions of user preferences.
[56]	Heuristic-based, User Sim: Graph theory, Aggr.: Sum of products	Pre-Filt.	Social	Music, E-retailing	Examines the context-aware recommendation as a search problem in the contextual graph.

Table 3: Characterization of collaborative filtering approaches

Appr.	Recommendation strategy	Paradigm	Context types	Domains	Means to incorporate context
[57]	Heuristic-based, User sim: Pearson correlation, Aggr: Sum of products	Pre-Filt.	Different types	General Application	Context information associated with users is exploited to infer individual user profiles and from these, the profiles of the groups.
[58]	Model-based, Tech: Matrix Fact.	Pre-Filt., Cont. Model	Location, Time	Hotels & Tourism	The original user-item rating matrix is divided into sub-matrices according to the temporal states. Then, each sub-matrix is factorized by considering location characteristics.
[59]	Model based:, Tech: Matrix Fact.	Pre-Filt., Cont. Model.	Location	Web services	Users and services are clustered into groups according to their location. These are then characterized according to their particular QoS features into a local user-service matrix. There is also a global user-service matrix where location is not considered. Matrix factorization is performed on the local and global matrices in a step-wise hierarchical linear process
[46]	Heuristic-based, User sim: Pearson correlation, Aggr.: Sum of products	Cont. Model.	Location, Time	Points of interest	Adopts an adjusted Pearson coefficient that computes similarities between users in different contexts. In order to do so, the approach defines a context similarity matrix that includes the coefficient between two users' current contexts for using an item. This coefficient is then incorporated into the aggregation function that computes the missing ratings.
[62]	Heuristic-based, User sim: Pearson correlation, Aggr.: Maximum	Cont. Model.	Location, Time	Points of interest	Recommends restaurants by computing the approximate time in reaching it, and considering distance, speed and road conditions. This approximation is included into the aggregation function.
[43]	Heuristic-based, Item sim: Cosine similarity, Aggr.: Maximum Heuristic-based, As. Rules: Apriori, Aggr.: Maximum	Cont. Model.	Location, Time	Points of interest, Music	Transforms the initial user-item matrix by integrating contextual factors as virtual items.
[67]	Heuristic-based, Item sim: Pearson correlation / Cosine Similarity, Aggr.: Sum of products	Cont. Model.	Human (mood), Time	E-learning	
[10]	Heuristic-based, User sim: Cosine similarity, Aggr.: Sum of products	Cont. Model.	Time, Human (intent of purchase: Personal-work, Gift Partner, Friend, Parent)	E-retailing	Considers virtual users under different contexts and finds neighbors of contextually similar users to infer recommendations.
[47]	Heuristic-based, User sim: Jaccard Similarity, Aggr.: Sum of products	Cont. Model.	Location, Time	Points of interest	Modifies the Jaccard similarity measure to incorporate context.

Table 3: Characterization of collaborative filtering approaches

Appr.	Recommendation strategy	Paradigm	Context types	Domains	Means to incorporate context
[63]	Heuristic-based, User sim: Pearson Coefficient, Aggr.: Sum of products	Cont. Model.	Social	General application	Integrates the strength of the relationships between telecom users into the similarity measure. This strength is modeled taking into account context information associated with phone calls such as duration, time of day and day of the week.
[9]	Model-based, User sim: Graph theory, Tech.: Matrix Factorization	Cont. Model.	Social	Movies	Combines the user-item rating matrix with user-user social contextual information from a trust network to generate a modified rating matrix. This last matrix is then factorized.
[84]	Model-based, Tech.: Matrix Factorization	Cont. Model.	Social	General application	
[85]	Model-based, Tech.: Matrix Factorization	Cont. Model.	Time	Movies	Consider context information to add biases on users and items into the recommendation model. Rating values are then influenced by context changes.
[45]			Time	Points of interest	
[86]			Time, Location	Movies	
[87]			Location, Time, Activity	Points of interest	
[91]			Social	Books, Music, Movies	
[92]			Social	General application	
[88]	Model-based, Tech.: Matrix Factorization	Cont. Model.	Time, Human (Hunger level, mood)	Food, Movies	Clusters items into groups according to the context of their consumption and treats them as virtual items associated with users in a new matrix that is then factorized. Missing ratings are inferred taken into account contextual information.
[89]	Model-based, Tech.: Matrix Factorization	Cont. Model.	Social	Books, Music, Movies	Considers context information to add biases on users and items into the recommendation model. Through matrix factorization, it creates a common latent factor space for users and items. In this representation space, users and items are clustered independently, so that they can then be brought back to a user-item rating matrix, where missing ratings can be inferred for groups of users.
[90]	Model-based, Tech.: Matrix Factorization	Cont. Model.	Human (age, gender)	Movies	Constructs several prediction models based on matrix factorization. Each model is then refined by taking into account the predictions from other models. Context information is considered to add biases on users and items into the recommendation model. Rating values are then influenced by context changes.

Table 3: Characterization of collaborative filtering approaches

Appr.	Recommendation strategy	Paradigm	Context types	Domains	Means to incorporate context
[73, 74]	Model-based, Tech.: Tensor Factorization	Cont. Model.	Time, Human, Social	Movies	Perform context-aware recommendations using tensor factorization, which considers the latent features of users and items, and the interaction of the user with an item under a given context. The latent feature of users, items and context types are stored in three matrices. Thus, the inference of preferences is computed as the inner product of the latent feature vectors of the matrices.
[75]			Time	Movies	
[76]			Location, Activity	E-retailing	
[77]			Social, Time	Movies, Food	
[78]			Social, Time	E-retailing, Movies	
[79]			Human (hunger level), Time, Location	Food	
[80]			Social, Time	E-retailing, Movies	
[81, 82]	Model-based, Tech.: Support Vector Machine (SVD)	Cont. Model.	Time, Social, Natural (weather), Location	Points of interest	Apply SVD to the ratings as represented in a user-item-context space to discriminate between recommended and not recommend items.
[83]	Model-based, Tech.: Support Vector Machine (SVD)	Cont. Model.	Location	Points of interest	
[94]	Model-based, Tech.: Bayesian Model	Cont. Model.	Time, Location, Human (mood)	Movies	By adopting a binary particle-swarm optimization technique, identifies the relevant contextual factors for user and item classes, and incorporates them into a latent probabilistic model.
[24]	Model-based, Tech.: Naïve Bayes	Cont. Model.	Time	Movies	Identifies which members of a household made some specific unidentified ratings of movies by considering time-context conditions such as hour of the day, day of the week and date of rating, as well as number of ratings given by a user. To do this, it analyses temporal trends using probability models.
[98]	Model-based, Tech.: Sparse Linear Method	Cont. Model.	Time, Location, Social	Movies	Models the contextual rating deviations of items, by assuming that there is a rating deviation for each <item, context condition> pair. This deviation is represented in a matrix, where each row represents an item, and each column represents an individual contextual condition. Then, the ranking score is estimated by an aggregation of user ratings on other items in the same context.
[99]	Model-based, Tech.: Linear Regression	Cont. Model.	Social, Time	Hotels & Tourism	Predicts user preferences using a linear regression model, which includes a value that represents the user context preference. This value can be computed by means of three different probabilistic methods: i) mutual information based method, ii) information gain based method, and iii) chi-square statistic based method.

Table 3: Characterization of collaborative filtering approaches

Appr.	Recommendation strategy	Paradigm	Context types	Domains	Means to incorporate context
[100]	Model-based, Tech: Matrix Fact.	Cont. Model.	Location, Social	Points of interest, Hotels & Tourism	Location of venues and user social network information are integrated into the matrix factorization model.
[64]	Heuristic-based, Item & User sim: Pearson correlation, Aggr: Weighted ad-hoc	Cont. Model.	Social	Web services	The level of trust among users (social context) is included in the weighted aggregation
[65]	Heuristic-based, User sim: Ad hoc, Aggr: Ad hoc	Cont. Model.	Location, Social	Points of interest, Hotels & Tourism	The social (relationships) and location context of the user is integrated into the process to measure the similarity between users.
[44]	Model-based, Tech: Matrix Fact.	Cont. Model.	Time, Activity, Location, Artificial	General application	Context-aware preferences as dimensions of the matrix
[93]	Model-based, Tech: Matrix Fact.	Cont. Model.	Social	E-retailing	Social context is considered in order to define groups of users with particular hyper-parameters used by the matrix factorization model
[68]	Heuristic-based, User sim: Cosine similarity, Aggr: Sum of Products	Cont. Model	Time, Social	General application	The prediction of user's preference is affected by the user-similarity , which is computed by considering the context (i.e, the social taggins)
[69]	Heuristic-based, User sim: Pearson correlation, Aggr: Sum of Products	Cont. Model	Time	Movies	Adds a time dimension to the original input data. It is defined in a new table which shows item ratings for an active user at different time-frames.
[70]	Heuristic-based, User sim: Cosine similarity, Aggr: Sum of products	Cont. Model	Time	Music	Infers user's preference by considering a context score, which is computed for each item in the recommendation list which shows the suitability of that item for the current context of the user.
[101]	Model-based, Tech: Random walk	Cont. Model.	Social	Social Networks	Tags from social networks are the basis for user similarity (Jaccard). Posts from users are compared by applying an ad-hoc similarity measure. A random walk algorithm is applied in order to estimate weights relating users to users in the social domain and users to items on auxiliary domains (web posts, videos, labels)
[102]	Model-based, Random walk	Cont. Model.	Time	Web services	Making time-aware personalized QoS prediction is important for high-quality web service recommendation because their performance is highly correlated with invocation time, since service status and network conditions are continuously changing. Time is integrated into a modified Pearson correlation similarity measure (similarities between users and between web services); time is also considered when making the final QoS prediction.
[103]	Model-based, Tech: Matrix Fact.	Cont. Model.	Social, Time	E-retailing	Social networking features of users (demographics, user posts, groups of related users, temporal activity preferences) that also interact with an unrelated e-commerce site can be transformed into latent factors that can be used for product recommendation, particularly for unknown new users of the e-commerce site.

Table 3: Characterization of collaborative filtering approaches

Appr.	Recommendation strategy	Paradigm	Context types	Domains	Means to incorporate context
[104]	Model-based, Tech: Matrix Fact.	Cont. Model.	Social	Retailing	The authors propose Social Poisson Factorization (SPF) probabilistic model that incorporates social network information into a traditional factorization method, assuming that each user's clicks are driven by their latent preferences for items and the latent influence of their friends (modeled as conditional probabilities). SPF also allows for generating explanations of recommendations based on the social relationships of users.
[105]	Model-based, Tech: Matrix Fact.	Cont. Model.	Social	Retailing	A probability based matrix factorization is proposed, taking into account trust relationships in a social network in the item recommendation process for retailing purposes. Users and items are then clustered using a Gaussian Mixture Model to enhance the recommendation performance.
[106]	Model-based, Tech: Matrix Fact.	Cont. Model.	Location, Social	Points of interest	The authors propose a probabilistic matrix factorization method which considers contextual information taken from a location-based social network, where each point of interest is described using a topic model, geographical and social correlations.
[66]	Heuristic-based, User sim: Jaccard similarity, Aggr: Heuristic graph based.	Cont. Model.	Social	Social Networks	The social features of folksonomies are used to provide a user with recommendations of similar users and resources. User profiles consider social contexts, by incorporating information of actions performed by the user on neighboring users' tags, and of other neighboring users on the user's tags. User neighborhoods are defined based on the social network friend relationships according to a specified length of the minimum path linking two users.
[71]	Heuristic-based, User-Sim: Ad-hoc, Aggr: Sum of products	Cont. Model.	Social	E-retailing	Adopts an ad-hoc similarity measure that computes similarities between users in different social context. This measure is then incorporated into the aggregation function that computes the missing ratings
[72]	Heuristic-based, User sim: Graph theory, Aggr.: Probability	Cont. Model., Post-Filt.	Time, Location, Natural (weather), Social	Movies, Hotels & Tourism	Proposes a graph-based contextual model framework. It examines the context-aware recommendation as a search problem in the contextual graph. It also includes a probabilistic-based post-filtering strategy to improve the recommendation results giving contextual factors.
[97]	Model-based, Tech: Matrix Fact.	Post-Filt.	Time	Movies	The authors propose two successive SVD matrix factorizations to further refine the latent factors for users and items independently, while using time context to filter out unfit items.
[95]	Heuristic-based, User sim: Cosine Similarity, Aggr.: Sum of products	Post-Filt.	Location, Time, Natural (weather)	Hotels & Tourism	Keeps track of contextual features of past user travels to each location. Context aware recommendations are inferred by finding the most similar users, calculating a score for each location, and filtering locations that do not meet contextual conditions.
[96]	Heuristic-based, Users sim: Pearson correlation, Aggr.: Sum of products	Post-Filt.	Time, Location	Points of interest	Adjusts inferred ratings to deliver contextual recommendations.

5.2.4. Findings

The information summarized in Table 3 suggests a correlation between the strategy used to generate recommendations and the paradigm used to incorporate context into the recommendation process of collaborative-filtering CARS.

In general, model-based approaches incorporate context using contextual modeling. This can be explained by the fact that models provide a more natural way to capture interactions between users, items and context. We also found papers reporting on the combination of model-based methods and pre-filtering strategies [42, 55, 58], or even the combination of the three strategies including contextual modelling [59]. However, these combinations may be risky since a pre-filtering strategy can cause loss of valuable information thus affecting accuracy [4].

Heuristic-based approaches are almost evenly distributed between the application of pre-filtering and contextual modeling strategies to realize context-aware recommendations. Regarding the application of pre-filtering, data sources are usually partitioned by context factors to improve data uniformity, which leads to stronger user/item similarities, as well as better confidence and support measures for association rules, thus improving the relevance of recommendations. In the case of contextual modeling, context information modifies how similarity is calculated.

With respect to contextual information, we found that most of the studied collaborative filtering systems have time, social, and location as the predominant factors. Furthermore, the application domains to which the surveyed systems are commonly applied are movies, restaurants, music, points of interests, social networks and e-retailing.

5.3. Hybrid approaches

Since hybrid approaches combine collaborative filtering and content-based recommendation methods in many different ways, there is not a unique abstract process that can characterize hybrid solutions the way we previously did for the non-hybrid processes depicted in Figs. 1 and 2. Table 4 presents the characterization of hybrid approaches, emphasizing on the way context is exploited.

As we found only five papers documenting hybrid RS, it is impossible to generalize their findings. Each approach follows its own strategy.

Table 4: Characterization of hybrid approaches

Appr.	Techniques	Paradigm	Context types	Domains	Means to incorporate context
[107]	Content-based Profile representation Item features	Pre-filt.	Time, Location	Movies, Music	Associate ratings with content-based attributes used to describe both user preferences and item features, and with the contextual factors gathered from the user experience (e.g., time of the day). Over the resulting vector space, the authors propose the application of several types of machine learning classification models.
	Collaborative filtering Model-based, Tech.: Naïve Bayes, Random forest, Multilayer Perceptron, and Support Vector Machine	Cont. Model.			
[108]	Collaborative filtering User sim: K-means	Pre-filt.	Location	Music, Points of interest	Takes into account user demographics: the geographical distance between the user and the event, and the subsequent time that it would take the user to arrive. It segments users into clusters, with every user having a probability of belonging to every cluster, and with each cluster having a probability distribution of liking every item. A discriminant filter evaluates the utility of the item for the user, considering a particular context.
	Content-based Profile representation Item features, Discr. filter Heuristic	Cont. Model.			
[28]	Collaborative filtering User sim: Pearson correlation, Heuristic-based Sum of products	Pre-filt.	Time, Location, Activity, Artificial (environment)	Movies, Music, News	Performs contextual recommendations by combining a discriminant filter with an aggregation of the ratings of similar users. A similarity measure between users takes into account their contextual profile.
	Content-based Profile representation Item features, Discr. filter Cosine similarity	Pre-filt.			
[109]	Content-based Profile representation: Item features	Cont. Model.	Social	Web Services	Identifies a couple of reading “experts” whose opinions can be regarded as guidance for news recommendation to particular individuals. Further, integrates this “expert” model with the content information and collaborative filtering, and propose a hybrid recommendation framework.
	Collaborative filtering Model-based, Tech: Matrix Factorization	Cont. Model.			
[110]	Collaborative filtering Model-based	Cont. Model.	Social, Location, Time	Social Networks	Social context is taken into account by considering the groups to which users belong to on an events-based social network. Users and events are described by the hour at which users attend events (time), and are compared by applying cosine similarity. Geographical preference of events is modeled by obtaining a probability density per user, taking into account the densities of attended events.
	Content-based Profile representation Item features, Profile comput. TF-IDF Discr. filter Cosine similarity	Pre-filt.			

5.4. Findings in the exploitation of context information

Figure 3 summarizes general findings related to the exploitation of context by the systems described in the surveyed articles.

Figure 3: Summary of findings in the exploitation of context information

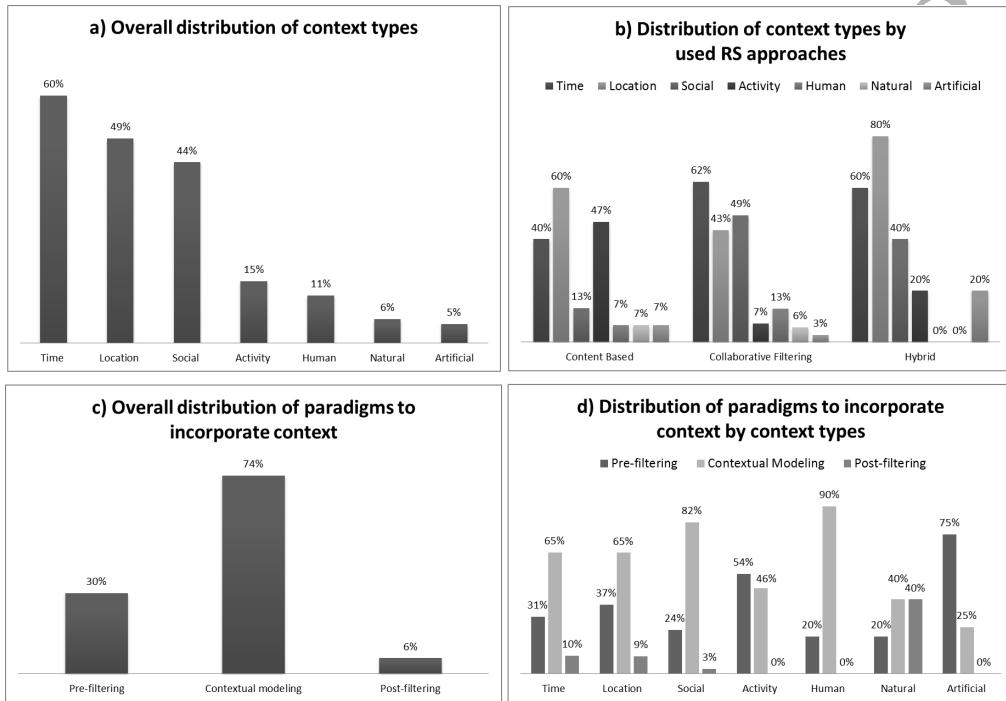


Figure 3.a presents the overall distribution of context types. According to this chart, time is the most used context factor followed by location and social information, whereas artificial is the less exploited context type followed by natural, human and activity. In the studied approaches, artificial context refers to data gathered from mobile sensors, natural context refers to weather conditions, and human context corresponds to user age, gender, mood, intent of purchase, preferences and hunger level. Only papers exploiting social context comment on the reasons why the exploited context type was selected. We hypothesize that, besides being relevant in all application domains, the main reason why time is the most exploited context type is that it is the easiest one to acquire: every system records information about transaction

dates, without requiring the explicit approval of users. As time context, location is also highly relevant and easy to acquire, however, its acquisition and usage, as in the case of social, activity and human context, requires user explicit approval. Artificial context does not necessarily compromise user privacy, however, its acquisition requires physical sensing infrastructures that are not always available.

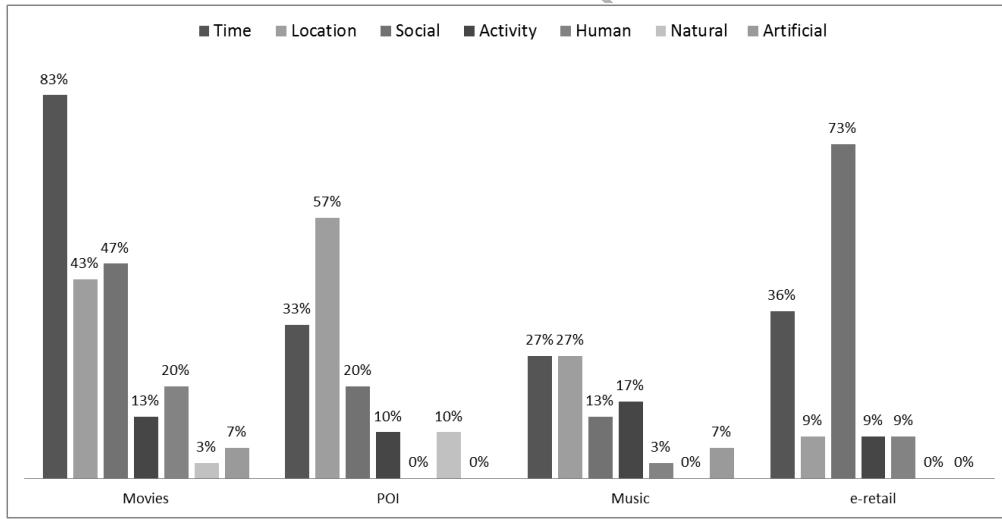
Regarding the context types used with the different recommendation approaches (i.e., content-based, collaborative filtering and hybrid), it is important to highlight that (cf. Fig. 3.b): i) only 13% of the content-based RS exploit social context. This is expected since social context emerges from the relationships among users, which are less relevant in content-based approaches; ii) location and activity are the most used context types in content-based RS. A reason for this is that the relationships existing between users and items usually emerge from the place where the item is used or bought, and the activity the user is performing while using an item. In addition, items are easily associated with places and activities; iii) time is the most exploited context type in collaborative filtering systems. This is probably associated with its easy acquisition, which becomes more relevant in collaborative filtering where it is required to characterize users under similar context situations; and iv) as expected, human context is more relevant in collaborative filtering than in content-based approaches, probably because demographic information is highly used in the analysis of user similarities.

Without doubt, contextual modeling, recognized by its effectiveness in improving the performance of recommendations, is the most common paradigm used to incorporate context into RS (cf. Fig. 3.c). Post-filtering, as discussed in previous subsections, is the less used, since its application may result on the discarding of time and space wise costly recommendations. Concerning the distribution of paradigms to incorporate context by context types (cf. Fig. 3.d), it is worth pointing out that systems exploiting activity (13 papers) and artificial (4 papers) context have pre-filtering as the predominant paradigm to incorporate context.

Most popular application domains identified in the studied papers are movies (30 papers, 34%), points of interest (POI, 18 papers, 21%), music (15 papers, 17%), and e-retailing (11 papers, 13%). Other domains are hotels & tourism (6 papers, 7%), web services (5 papers, 6%), news (4 papers, 5%), food (3 papers, 3%), indoor shopping (2 papers, 2%), social networks (2 papers, 2%), and e-learning (1 paper, 1%). Seven of the studied papers do not report targeting particular application domains (general application).

Figure 4 presents the distribution of context types by application domains. Movies is the only domain that exploits all context types, being time, social, and location the most exploited ones. As expected, location is the most common context type in the points of interest domain, followed by time. Concerning the music domain, location, time and activity are the most used context types. Activity is more predominant in this domain than in the others, probably because music genres are commonly associated with specific user activities. In the e-retailing domain, social is the predominant context type, followed by time. Here it is evident the influence of collaborative filtering as the predominant type of recommendation algorithm, particularly in this domain. Context types location, activity and human are equally exploited in e-retailing applications. Finally, it is worth also noticing that natural context, which in general refers to weather conditions, is more used in points of interest applications.

Figure 4: Distribution of context types by most popular application domains



6. Characterization of validation methods

The improvement of user experience is the ultimate goal of a recommender system. In order to measure it, a series of properties, each with

a set of metrics, have been proposed and used since the first developments in the field. These properties allow us to determine the pertinence of the recommendations being suggested. Instances of these properties are predictive power, confidence, diversity, learning rate, coverage, scalability and user evaluation [111].

In this section we summarize the properties that were considered to evaluate the recommendation systems documented in the surveyed papers, particularly predictive power, which is the most commonly used evaluation property. The first two parts of this section focus on prediction metrics and evaluation protocols identified in the studied articles. Then, we summarize other properties that were also used to assess the quality of recommendations in the studied CARS. Finally, we present the list of datasets that we identified in our survey.

6.1. Prediction metrics

Among the different metrics that can be considered to evaluate RS, the most commonly used is predictive power. This could relate to the information retrieval origins of RS. All but five of the papers we surveyed use some kind of prediction metric to assess the quality of their recommendations.

Table 5 presents the distribution of the reviewed articles with respect to prediction metrics. The first column represents the class of metric. The second column refers to the specific prediction metric techniques, grouped by their class. The third column presents the number of papers that use the metric to validate the proposal, which are listed in the last column. It is important to note that some articles may use more than one prediction metric to evaluate their approach. We borrowed the definitions of these metrics from [111] and [112].

Prediction metrics are based on different types of comparisons between the recommended items and the accessed or consumed items. As mentioned in [111], there are three classes of prediction metrics: rating prediction, usage prediction and ranking metrics (cf. first column of Table 5).

Table 5: Metrics used to evaluate predictive power

Class	Prediction Metrics	#Approaches	Approaches' references
Rating prediction metrics	MAE	27	[4, 9, 42, 46, 47, 50, 51, 59, 63, 69, 73, 77, 79, 80, 84, 88, 89, 91, 92, 93, 96, 100, 101, 102, 103, 105, 106]
	RMSE	24	[9, 10, 47, 56, 71, 77, 78, 79, 80, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 100, 101, 105, 106]
Usage prediction metrics	Precision	43	[4, 10, 24, 27, 28, 29, 32, 33, 36, 39, 40, 41, 42, 43, 44, 47, 51, 53, 54, 56, 58, 60, 62, 63, 65, 66, 67, 70, 71, 72, 75, 80, 82, 83, 84, 95, 97, 98, 101, 103, 106, 107, 109]
	Recall	28	[4, 10, 29, 33, 40, 42, 43, 44, 50, 53, 54, 58, 62, 63, 65, 67, 70, 71, 72, 75, 82, 84, 97, 98, 101, 103, 106, 109]
	F-measure	10	[4, 10, 29, 33, 40, 43, 57, 62, 67, 97]
	AUC	5	[24, 60, 74, 103, 107]
	MAP	8	[24, 34, 55, 76, 79, 95, 98, 103]
	BR	1	[95]
Ranking metrics	NDCG or DCG	9	[30, 31, 35, 47, 57, 72, 74, 87, 110]
	Hit Ratio	6	[48, 68, 70, 74, 87, 99]
	MRR or CRR	3	[99, 103, 104]
	Map@K	1	[101]
	Rt10	1	[35]
	None or other type reported	5	[37, 45, 49, 52, 81]

Rating prediction metrics. These metrics measure the correctness of the recommendations in terms of their error. The two metrics we identified in the studied articles are *root mean squared error* (RMSE) and *mean absolute error* (MAE). These metrics measure the distance between predicted and real ratings. So, lower values of RMSE and MAE indicate a higher predictive power. Since RMSE squares the error, it tends to penalize large errors more heavily. The choice between RMSE and MAE is at discretion of the developer. For instance, in the movies domain, while in [85] the RS is evaluated by measuring the quality of suggestions using RMSE, giving more importance to larger differences between the predicted and real ratings, in [73] the evaluation is based on MAE, considering a linear approach to measure the errors.

Usage prediction metrics. These metrics are based on different types of proportions between recommended and consumed items, as determined

by the contingency table that compares them. The following are the usage prediction metrics that we identified in the surveyed papers:

- *Precision (or true positive rate)* measures the proportion of recommended items that result relevant to the users, that is, those recommended items that the user actually consumes. The CARS proposed in [39] is evaluated with respect to a context-free approach using this metric. This system exploits user location (i.e., a gym, the library, the office, the transportation system) to suggest appropriate songs. The results show that the proposed approach outperforms its baseline (e.g., a precision of 60% and 50%, respectively, in situations where the location context corresponds to the transportation system).
- *Recall (or sensitivity)* measures the proportion of consumed items that were correctly recommended, that is, the fraction of items relevant to the user that were suggested by the system. Recall and precision are usually considered together as two facets of the quality of the recommendation. An example is presented in [53], where precision and recall are used as the basis to show that the greater the cardinality of a set of recommended items is, the higher the value of recall is.
- *Specificity (or true negative rate)* measures the proportion of not recommended items that are irrelevant to the users. This metric was not directly used in any of the surveyed papers, but it is a basis for the definition of other metrics such as AUC, explained below.
- The *F-measure* family of metrics combines precision and recall, allowing for the comparison of different RS using a single metric. Adomavicius et al. [4] use this metric to compare the effects of taking into account independent context factors (i.e., social, time and location), or combinations of them, when predicting user ratings. The results showed that the segments theater-weekend (i.e., location-time), theater (i.e., location), and theater-friends (i.e., location-social) substantially outperform the standard methods in terms of F-measure. They also applied F-measure to show how their approach outperforms regular non-context RS.
- *AUC (or area under the curve)* is a more robust metric that considers the variations between the true positive rate (recall) and the true

negative rate ($1 - \text{specificity}$). The movie CARS published in [74] is evaluated using this metric.

- Other usage prediction metrics are refinements of simpler ones, such as *mean average precision* (MAP) [55], or *benefit ratio* (BR) [95]. The latter is defined as the ratio between the number of users who get an improved prediction and the number of users who get a deteriorated prediction.

Ranking metrics. These metrics assume that the utility of a recommended item is proportional to its position in the ordered list of recommendations produced by the RS. The ranking metrics used to evaluate the CARS included in our survey are the following:

- *Normalized discounted cumulative gain (NDCG)* and *discounted cumulative gain (DCG)* consider that highly ranked relevant objects give more satisfaction than poorly ranked ones. Biancalana et al. [30] use NDCG to compare their CARS performance with the performance of other approaches. They also study the effect on the quality of recommendations, as measured by NDCG, by taking into account different contextual factors separately. Biancalana et al. [30] and Hong et al. [53] argue that CARS produce better results when the number of items to recommend increases.
- *Hit ratio* measures whether a user's target choice appears in the top- K recommendation list. Generally denoted as Hit@ K , where K indicates the number of recommended items. Unger et al. [87] find that the use of latent context models provides a noticeable advantage over non-contextual models for almost every value of K . The advantage is greater with small values of K (i.e., ranging from 1 to 4), which means that the latent context model is highly capable of ranking a suggested recommendation according to the user's current context.
- *Mean reciprocal rank (MRR)* and *Cumulative reciprocal rank (CRR)* evaluate the ranking position of a user's target choice in the recommendation list. Chen and Chen [99] use CRR to evaluate recommendations that take into account location context.
- *Mean average precision (MAP@K)* considers the precision of the first K recommended ranked items. Every item on the list of ranked items

contributes to the MAP@K measure of the recommendation proportionally to its position, if they were indeed accessed/consumed by the user for which the recommendations were made. Jiang et al. [101] use this metric, along with other metrics (MAE, RMSE, Precision, Recall, F1 measure) to evaluate the performance of different configurations of their proposed model.

- *Rt10* averages the ratings of the top 10 recommended items. It is used specially in information retrieval. Son et al. [35] show, using the Rt10 metric, that news article recommendations are more effective when considering their particular geographical location.

Finally, from the five papers that do not report the usage of a particular prediction metric, two of them use other mechanisms to evaluate their models. For instance, to evaluate user satisfaction, Hong et al. [37] measure effectiveness and usability, whereas Baltrunas et al. [45] use a standard usability questionnaire. The approach presented in [81] is compared to a baseline model in terms of accuracy without reporting any metrics. However, these authors published the same model in [82] including a quantitative evaluation.

6.2. Evaluation protocols

This subsection presents the different evaluation protocols applied by the authors of the surveyed papers. These protocols define the way data sets are handled and partitioned into training and test sets to evaluate the quality of the recommendations. We found that in all reported cases context was consistently considered as a data set partitioning criterion, and that the baseline approach is usually a context-free RS, or a CARS that follows a different approach than the one being proposed.

Table 6 presents the distribution of reviewed articles with respect to evaluation protocols. The first column lists the evaluation protocols, the second column shows the number of papers that use the protocol to validate the proposed CARS, and the third column specifies each of the corresponding surveyed papers. Papers [33, 41, 56, 103] did not report on the used evaluation protocol.

Table 6: Evaluation Protocols

Evaluation Protocols	#Approaches	Approaches
Holdout or cross-validation	46	[9, 10, 28, 31, 32, 33, 39, 45, 48, 54, 57, 58, 59, 60, 62, 63, 65, 66, 67, 68, 69, 70, 71, 72, 75, 76, 78, 79, 81, 82, 84, 87, 91, 92, 93, 94, 96, 97, 100, 101, 102, 104, 105, 106, 109, 110]
K-fold cross validation	21	[4, 30, 34, 38, 42, 43, 44, 47, 51, 55, 73, 77, 80, 83, 86, 88, 89, 90, 95, 98, 107]
Hypothesis test	5	[27, 35, 40, 46, 99]
Bootstrapping	2	[4, 29]
Simulation	1	[64]
None reported	4	[33, 41, 56, 103]

Holdout or cross-validation. This is one of the most commonly used evaluation protocols. It consists in splitting the dataset into two sets: training (e.g. 70% of the data) and test (30%). The recommendation model/algorithm is trained using the first set, and evaluated using the second one. The training and test data can be obtained in different ways, depending on the application domain and the way context information affects the recommendations. For example, in [39], Cheng and Shen evaluate their music CARS by splitting the data set according to time and location context, before extracting the training and test sets.

K-fold cross-validation. This is a more sophisticated evaluation protocol that consists in partitioning the dataset into K equally sized groups of items called folds, to then perform a cross-validation evaluation process. One of the folds is chosen as the test set and the union of the other folds as the training set. This process is repeated K times, each time changing the fold used as test set. This evaluation protocol is used to evaluate the CARS presented in [42]: for each fold, the authors compute the MAE, precision and recall metrics, and average their results to then estimate the quality of their recommendation model. The CARS proposed in [86] and [4] apply independent recommendation processes for each relevant context. The authors evaluate the performance of these systems using K-fold cross-validation. This allows them to compare the predicted ratings for each context, and establish the contexts for which the recommendation is more accurate.

Hypothesis test. This protocol uses statistical inference. It is based on the computation of the statistical significance of the differences between the

compared CARS. In particular, it is useful to identify whether there is a significant difference between contextual and non-contextual recommendations. The CARS presented in [99] is evaluated using this protocol, where the hypothesis is that user preferences are influenced by contextual factors, and that the proposed recommendation algorithm is capable of capturing such influences. For example, user restaurant preferences may not be influenced solely by aspects such as food quality, value, and service, but also by contextual factors such as location.

Bootstrapping. This protocol relies on random sampling with replacement. That is, a subset of size N is taken from the original data set and then partitioned into training and test data. This process is repeated multiple times, considering always the whole original data set as the basis for the re-sampling. The estimation of the performances of the RS is finally aggregated from the results of each re-sample. For instance, Musto et al. [29] use a bootstrapping-based protocol proposed in [4]. This protocol consists in identifying different possibly overlapping subsets of the dataset based on context types (e.g., establishing a contextual segment composed of time context observations, or another one composed of location context observations). The authors extract 500 random re-samples from their dataset and split them by assigning 29/30th of the items to the training set and 1/30th to the test set. They use precision, recall and F1 as the metrics to evaluate the performance of their system with respect to the different contextual segments.

Simulation. When there is no dataset available upon which to perform the evaluation of the recommendation model, it is possible to generate an artificial synthetic dataset using simulation techniques, based on certain suppositions (e.g. normal distributions). Eirinaki et al [64] applied this method to generate a social network simulating trust relationships between users (social context), and the matrix relating users to items (in their case, web services).

6.3. Other properties

Predictive metrics measure how close predicted preferences are from user real preferences. However, predictive power is not enough to measure whether the recommendation was satisfactory, useful or effective to the users [112]. A recommendation system may be highly accurate, but only for those items for which a recommendation may result useless (e.g., products that the user buys very frequently).

Table 7 presents the approaches that consider properties other than predictive power to evaluate the proposed CARS. The plus sign in a cell indicates that the corresponding property is used to evaluate the CARS proposed in the paper represented by the row (cf. first column of the table). As in the case of the prediction metrics presented above, we borrowed the definition of these properties from [111] and [112].

Table 7: Other properties

Appr.	Learning rate	Confidence	Diversity	Novelty	Coverage	Scalability	Usability
[76]	+						
[98]	+						
[86]	+						
[90]	+	+	+				
[62]		+				+	
[94]			+		+		
[66]				+			
[53]						+	
[79]	+					+	
[99]	+						+
[30]							+
[27]							+
[38]							+

Learning rate. This property measures how fast an algorithm produces good recommendations. Learning rate is also associated with the parameter that determines how fast or slow a recommendation model will converge towards an optimal solution. We found that all of the CARS evaluated through this property are based on model-based strategies (i.e., matrix and tensor factorization, and linear regression), and exploit context information by implementing the contextual modeling paradigm.

Confidence. This property refers to the trustworthiness of the system predictions, and the extend to which they help users make more effective decisions. The work published in [90] uses this property to evaluate, under specific contexts, the quality of several prediction models based on matrix factorization,

Diversity. This property measures how dissimilar are the recommended items among them. It is defined as the opposite of similarity. Zhang et al.

evaluate the quality of their movie CARS in terms of diversity [90]. They argue that a good recommender system is the one that delivers considerable different recommendations, for example, films belonging to different genres.

Novelty. Based on the assertion that the relevance of a recommended item depends not only on its correctness, but also on its novelty. Nocera et al. [66] define an ad-hoc measure that takes into account whether the recommended items were already known to the user (e.g. accessed in the past).

Coverage. This property measures the proportion of items that the system recommends from the universe of available items. Not all of the available items are subject to be recommended. This is the case of collaborative-filtering RS for items that have not been yet consumed or rated by the users. Sitkrongwong et al. measure accuracy and coverage for different contextual factors [94]. They found that, since not every context applies to all items, it is possible to increase the coverage by ignoring some of the relevant contextual factors. Nevertheless, there is a trade-off between accuracy and coverage that can be mitigated by identifying the set of relevant contextual factors for each user and each item separately, instead of identifying the relevant contextual factors for the entire data set.

Scalability. This property refers to the computational capability of the recommender system to handle a growing amount of data. Khalid et al. address this property by storing and processing data on geographically distributed nodes [62]. Shi et al. measure scalability in terms of time complexity [79]. We did not find any relation between context and scalability.

Usability. This property measures the satisfaction of the user with respect to the ease of use of the RS. In [27], Hawalah and Fasli evaluate usability through a questionnaire that asks users to rate a set of statements, including some to evaluate the contextual nature of the system: i) *the items recommended to me matched my interests*, ii) *the items recommended to me took my personal context requirements into consideration*, and iii) *I was only provided with general recommendations*.

6.4. Data sets

Table 8 characterizes the 16 data sets that we identified as publicly available from 32 out of the 87 characterized papers. For each data set, we indicate the papers that use it, the domain, and the supported context types.

Table 8: Data sets identified in the SLR

Appr.	Domain	Brief description	Context types	URL
[73]	Movies	Information about movies, users and ratings.	Human (age, gender)	https://research.yahoo.com
[9, 50, 57, 60, 75, 78, 80, 90, 97]	Movies	MovieLens: information about ratings, users, and items (movies).	Human (age, gender, occupation), Time (day, month, year, hour, minute, second)	http://grouplens.org/datasets/movielens
[72, 86, 88, 94]	Movies	Data set collected for experiments using an on-line application for rating movies. Users fill in a simple questionnaire created to explicitly acquire the contextual information describing the situation during the consumption. It contains records of users, ratings and movies.	Time (season, day type), Location, Natural (weather), Social	http://students.depaul.edu/yzheng8/DataSets.html
[85]	Movies	Provided by the Netflix Prize. It contains records of ratings, users, and movies.	Time	http://www.netflixprize.com
[24]	Movies	CAMRa 2011s MoviePilot Dataset: contains ratings, users, and items.	Time	http://2011.recsyschallenge.com/dataset
[36, 48]	Music	Information about users, artists, bi-directional user-friend relations, and user-listened artist relations	Social, Time (day, month, year)	http://grouplens.org/datasets/hetrec-2011
[54, 58, 62, 65, 100, 106]	Points of interest, Hotels & Tourism	Data set acquired from FourSquare. It contains information places.	Location, Social	https://sites.google.com/site/yangdingqi/home/foursquare-dataset
[68]	General application	Information about users, tagged papers, and tags.	Time, Social	http://www.citeulike.org/faq/data.adp
[69]	Movies	Provided by the Comaq Systems Research Center. Ratings given by users to movies.	Time	http://www.research.compaq.com/SRC/eachmovie
[65]	Points of interest, Hotels & Tourism	Friendship network with information about locations and user check-ins (user, check-in time, latitude, longitude, location)	Social, Location	http://snap.stanford.edu/data/loc-gowalla.html
[57]	General application	Information of ratings given by users to jokes	Human (user preferences)	http://eigentaste.berkeley.edu/dataset/
[71, 91, 93, 105]	E-retailing	Information about reviews of products done by users	Social	http://www.trustlet.org/opinions.html
[70, 93]	E-retailing, Music	Information about reviews of products done by users	Social, Time	https://labrosa.ee.columbia.edu/millionsong/lastfm
[91, 92, 93, 105]	E-retailing, Books, Music, Movies	Information about user reviews and recommendation services for movies, books, and music	Social	http://socialcomputing.asu.edu/datasets/Douban

7. The effect of incorporating context into RS

When conducting an SRL on CARS, a natural question is the level of improvement of RS performance (e.g., in terms of accuracy) obtained from the

inclusion of a particular context type into the recommendation process. Nevertheless, answering this question results impractical, given the wide spectrum of recommendation techniques that can be combined with the different context types, through any of the three existing paradigms to include context information into RS. Furthermore, the performance of these systems vary depending on the used dataset and evaluation metrics, which make the results incomparable. For this reason, questions such as *what is the context type that provides the best results for improving recommendations in a particular context domain?* were not included in the set of research questions that drove the development of this SLR.

Despite the limitations to compare the effectiveness of particular context types, we surveyed the impact of incorporating context information into the reported systems. We found that only 36 out of the 87 studied articles quantitatively evaluate the obtained improvements with respect to baseline approaches (cf. Table 9). This constitutes an opportunity for this research community—formal validations and benchmarks of CARS are of paramount importance to advance this field. The systems reported in these 36 papers were all evaluated with respect to at least one baseline approach in terms of accuracy, through any of the metrics listed in Table 5.

Table 9 presents the improvements reported by these papers. For each approach (cf. Column *Appr.*) the table includes the types of context exploited by the corresponding CARS, the application domain, and the improvement obtained for each of the used metrics. The table groups accuracy metrics according to the three metric categories (i.e., usage prediction, rating prediction and ranking prediction), explained in Sect. 6.1. The goal of this table is to report the surveyed information rather than to provide a basis for comparing the improvements obtained in RS when including the different context types.

Table 9: The effect of incorporating context into the RS that were evaluated quantitatively

Appr.	Types of context	Application domains	Usage Prediction				Rating Prediction		Ranking Prediction
			Precision	Recall	F-Measure	MAP	MAE	RMSE	
[67]	Human(mood), Time	e-learning	2%	2%	5%				
[50]	Time, Location	Movies		22%			32%		

Table 9: The effect of incorporating context into the RS that were evaluated quantitatively

Appr.	Types of context	Application domains	Usage Prediction				Rating Prediction		Ranking Prediction NDCG, Hit Ratio, MRR
			Precision	Recall	F-Measure	MAP	MAE	RMSE	
[90]	Human (age, gender)	Movies						3%	
[99]	Social, Time	Hotels and Tourism							
[79]	Human (hunger level), Time, Location	Food				15%	9%	9%	
[80]	Social, Time	E-retailing, Movies	6%				17%	14%	
[47]	Location, Time	Point of interest	Between 1,7% and 3,1%				9%	4%	
[51]	Time, Location, Social	Movies	10%						
[72]	Time, Location, Natural (weather), Social	Movies, Hotels and Tourism	Between 80% and 200%; and between 16% and 103%						
[29]	Time, Social, Location	Movies			About 10%				
[98]	Time, Location, Social	Movie	Between 2% and 42%				Between 2% and 6%		
[43]	Time, Location	Music, Point of interest	Between 5% and 33%	Between 5% and 33%	Between 5% and 33%				
[75]	Time	Movies		Between 30% and 35%					
[73]	Human(age, gender), Time, Social	Movies					Between 5% and 30%		
[84]	Social	Not Identified	Between 12% and 22%		About 21%			About 24%	
[76]	Location, Activity	e-retailing	About 53%			About 40%			
[87]	Location, Time, Activity	Point of interest							Hit ratio: About 25%
[68]	Time, Social	General application							Hit ratio: Between 34.56% and 35.91%
[93]	Social	E-commerce					About 10%	About 10%	

Table 9: The effect of incorporating context into the RS that were evaluated quantitatively

Appr.	Types of context	Application domains	Usage Prediction				Rating Prediction		Ranking Prediction NDCG, Hit Ratio, MRR
			Precision	Recall	F-Measure	MAP	MAE	RMSE	
[91]	Social	Books, Music, Movies					Between 9% and 18%	Between 7% and 17%	
[58]	Social	Books, Music, Movies	Avg: 73.27 times better	Avg: 73.27 times better					
[69]	Time	Movies					About 5%		
[92]	Social	General application					Avg: 21%	Avg: 18%	
[31]	Human (user interest)	Web services							NDCG: 40%
[32]	Social	Multimedia	About 25%						
[100]	Social, Location	Points of interest, Hotels & Tourism					Best case: 22%	Best case: 35%	
[65]	Social, Location	Points of interest, Hotels & Tourism	Best case: 15%	Best case: 10%					
[110]	Social, Location, Time	Social networks & Tourism							NDCG: 60%
[101]	Social	General application					Between 10% and 27%		
[59]	Location	Web services					Between 2% and 3%		
[102]	Time	Web services					Between 5% and 20%		
[104]	Social	E-retailing							MRR: between 8% and 25%
[56]	Social	E-retailing	Best case: 78%						
[57]	Different types of context	General application	Best case: 78%						DCG: Between 2.5% and 5%
[106]	Social, Location	Points of interest					Best case: 12.6%	Best case: 14.5%	
[105]	Social	E-retailing					Best case: 16.24%	Best case: 16.09%	

8. Research opportunities

This section provides CARS researchers with a list of research opportunities, most of them borrowed from the studied articles. From each paper, we identified, categorized, and analyzed the challenges that authors defined as worthy of future work. Each subsection corresponds to one of the nine challenge categories that we identified: *dynamic context management, context gathering, context reasoning, contextual modeling, problems inherent in RS, CARS evaluation, users in the loop, self-adaptation and privacy and ethical considerations*.

8.1. Dynamic Context Management

Traditional CARS assume that context information is immutable over time, even when user situations continuously change. Evidence of this are deal recommendation systems that keep sending offers to the user for events currently happening in her home city, despite she is in a several day business trip that is scheduled in her agenda, and the user's agenda as well as her current location can be easily monitored by modern applications [7]. This static vision of context information causes that RS deliver recommendations that are irrelevant to users, which has negative effects for businesses.

To deal with this dynamic nature of context, CARS must be equipped with runtime mechanisms to identify relevant context and integrate it into the recommendation process dynamically [3, 5]. This implies also to enable RS to manage the life cycle of context information at runtime, for instance, to identify context variables that become relevant or irrelevant, and treat them accordingly. For example, by adapting the recommendation model according to new context variables that may become relevant while the user interacts with the system.

Dynamic context management research in RS includes investigating mechanisms to i) identify context changes that affect the relevance of recommendations; ii) characterize the life cycle and dynamics of context information; and iii) develop situation-aware and self-adaptation mechanisms to enable CARS with the ability to adjust recommendation models at runtime. Among the studied papers, [3, 28, 30, 36, 47, 69, 85] declare dynamic context and its management challenges as a future research area.

The following two categories of research opportunities, context gathering and context reasoning, are completely related to dynamic context management, since they are concrete phases of the context information life cycle [5].

8.2. Context Gathering

Context gathering refers to the process of acquiring context information from the user's environment. When the relevant context is dynamic (e.g., context that changes over time such as the purchase intent of a user), context acquisition requires automatic mechanisms to detect context sources that become available at runtime, and deploy the sensors required to gather this information. Context gathering challenges include: i) the acquisition of context information from non-explicit and non-traditional context sources (e.g., to identify user intents and motivations); and ii) the development of user interfaces that allow the acquisition of relevant context, without requiring user explicit inputting through traditional interfaces. The authors of the following papers highlight the importance of context gathering research [27, 40, 45, 48, 60, 76, 84, 96].

8.3. Context Reasoning

Context reasoning refers to the inference of implicit context facts from raw context [5]. When context is highly dynamic, context management mechanisms must support the addition of reasoning rules dynamically. Context reasoning challenges in RS include: i) inferring context facts from the combination of different context variables; ii) understanding, particularly at runtime, the relationships between context situations and user preferences; and iii) exploiting context available in user profiles effectively. Authors of papers [4, 30, 39, 45, 52, 58, 82, 86, 107, 108] identify context reasoning as a relevant research topic.

8.4. Contextual Modeling

Pre-filtering, contextual modeling and post-filtering are the three existing paradigms to incorporate context into RS. In contextual modeling, context information is directly integrated into the recommendation model, which, in many cases, has been proved to be more effective than pre- and post-filtering approaches. As a result, an important number of researchers investigate how to exploit context information through contextual modeling [4, 24, 30, 41, 43, 51, 56, 68, 73, 79, 81, 86, 91, 105, 106]. Contextual modeling challenges include the development of new techniques and mechanisms to: i) integrate context into traditional recommendation models; ii) improve rating estimation methods by exploiting context; and iii) identify the context variables that must be integrated into the recommendation model.

8.5. Problems inherent in RS

Context information can be also useful to solve specific problems in RS. Such is the case of the cold-start, self-biased recommendations, and sparsity problems. Concerning the cold-start problem, context provides information that allows the characterization of users, even when they are newcomers to the system [38, 39, 93, 109]. Regarding the self-biased problem, an important challenge is to develop mechanisms to prevent the self-influence of frequently recommended items on future recommendations; the approach presented by Nocera et al. [66] deals with this problem using a novelty metric that considers social context. Concerning the sparsity problem, context-dependent matrices could help decrease sparsity by taking into account different subsets of dimensions under particular context situations [56, 59, 88, 92, 93, 101, 102, 109]. For example, to infer user ratings in a department store, instead of taking into account all of the products the user has bought in the past, one could use only those products directly associated with the user's current purchase intent (e.g., vacation planning, back to school season).

8.6. CARS evaluation

The evaluation of new methods and techniques is crucial to advance the state of the art of CARS, and to confidently apply new developments in real life. Major evaluation challenges identified from the studied papers are [29, 36, 46, 51, 64, 69, 76, 107]: i) the investigation of new properties and metrics; ii) the development of benchmarks that facilitate the understanding of approaches that perform better in particular circumstances; iii) the development and documentation of real life experiments in different application domains; and iv) the acquisition of contextual real data to improve the quality of validations.

8.7. Users in the loop

There is an increasing tendency to conceive users as part of software systems, instead of entities that simply interact with systems. This is commonly known as *the integration of users in the loop*. Users can be integrated in the recommendation process, at one or several of its phases, for example, through feedback that can be used to improve recommendations. Users in the loop are also valuable sources of relevant context. An important challenge is to achieve a seamless integration to avoid affecting the natural behavior of the user. This challenge category was explicitly addressed in [50].

8.8. Self-adaptation

Self-adaptive software systems adjust their structure or behavior at runtime to control the satisfaction of functional and non-functional requirements [113]. To achieve these dynamic capabilities, these systems are instrumented with feedback loops that measure outputs and compare them against reference inputs. If the measure output does not correspond with the desired value specified in the reference input, a controller adjusts the target system to obtain better results [114]. An interesting research direction for the advancement of recommender systems is to instrument them with feedback loop-based mechanisms that allow them to self-improve at runtime. Authors of paper [33] highlight self-adaptation as a promising research direction. In particular, they are interested in implementing a feedback mechanism that adjusts the semantic similarity metric at runtime with the goal of improving performance.

8.9. Privacy and ethical considerations

Privacy and ethics are important aspects to be considered in CARS. Several relevant challenges arise from the need to assure these aspects, which is particularly difficult at runtime. For example, whenever a new context source is identified as relevant, how to validate with the user that this information can be used by the system, that this usage is transparent to the user, and that this information will be used only for the purposes approved by the user. Privacy and ethical aspects are of paramount importance to develop confidence and trust in the use of personalization in CARS [27].

9. Conclusions

This paper presented a comprehensive characterization of context-aware recommendation processes and systems, based on the findings of a systematic literature review (SLR) we conducted to survey CARS that were published between 2004 and 2016. This study was conducted with the goal of helping practitioners and researchers understand how context information can be effectively combined with recommendation mechanisms. The main results provide a clear understanding about where context information is usually integrated into the recommendation process, the techniques available to exploit context information depending on the underlying recommendation approach and the phase of the process where context is included, the context types more frequently exploited in the different application domains, and the most

common used evaluation mechanisms, including properties, metrics and protocols.

Despite the comprehensiveness of this study, it is unfeasible to conclude about the effectiveness of using particular context types in specific application domains. This is in part because the effect of including context into RS is difficult to generalize given that the results depend on the nature of the used data sets and recommendation approaches. Furthermore, validation methods must be improved to include quantitative measures that allow a more objective evaluation of the proposed approaches—36 out of the 87 studied papers evaluate their systems quantitatively by comparing, against other approaches used as baselines, the improvements obtained with the integration of context information into the recommender system.

Besides the need for improving validation methods, this survey exposes also several research challenges that deserve further investigation. In particular, those related to the need for i) instrumenting CARS with runtime mechanisms to manage context dynamically along its life cycle; ii) developing new techniques to exploit context directly into the recommendation model; iii) exploiting context to solve inherent RS problems, in particular, the cold-start, self-biased recommendations, and sparsity problems; iv) instrumenting RS with self-adaptation capabilities, and v) solving user-oriented issues such as their better integration in the recommendation loop, as well as the privacy and ethical considerations that arise.

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Construction of Recommender System based on Cognitive Model for “Self-Reflection”

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ABSTRACT

Every human processes a set of mental schemas for problem solving. We develop and improve these schemas by reflecting on our experiences with errors, which is a type of metacognition (Kayashima, 2008). In this study, we proposed a cognitive model of this “self-reflection” process based on Kayashima’s two-layer working memory model, and developed a food recommender system using our cognitive model. In the test simulation, the users were satisfied with the foods that the system recommended, although the recommendation results were unexpected to the users. This implied the system practically worked to satisfy the user’s expectation. On the other hand, the candidate recommendations which the system selected as its final output were different from those provided by the users. This suggests that the cognitive model needs improvement in terms of psychological reality.

Author Keywords

self-reflection; cognitive model; recommender system; meta-cognition.

INTRODUCTION

It is important for human beings to acquire problem solving skills to deal with the various problems that they face each day. Metacognition can be defined as the human ability to acquire such problem solving skills [1, 2]. By using metacognition, human beings can observe and improve the problem-solving strategies that they apply. In general, humans avoid committing the same mistakes by improving their strategies. However, it is not clear how people use failure experiences for metacognition and how they improve problem-solving strategies. In this research, we define the refinement of problem-solving skills based on human failure experiences as self-reflection, and attempt to construct a cognitive model expressing the self-reflection process.

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Self-reflection is a cognitive activity that is performed internally. We aim to construct a cognitive model expressing the self-reflection process, oriented towards the constructive approach. In this study, we deal the task of food recommendation. Generally, in this domain, it is difficult for the recommender system of a content-based filtering method to make unexpected but satisfying recommendations to the user. This problem is caused by the fact that human preferences are dynamic, even if the system builds a preference model based on the user’s history. In this case, the self-reflection function should be able to modify the system to adapt to the user’s preferences.

PROPOSED MODEL

Kayashima’s model for problem solving: Two Layer Working Memory Model

Many literatures have dealt with metacognition, especially the learning support for metacognitive activities in the field of Artificial Intelligence in Education and Learning Science. Kayashima et al. [3] provided an explicit description for metacognitive activities and proposed the two-layer WM model. This model provides an explanation for the mechanism of cognitive operation (e.g. observation) to cognitive activity, and in this point, this model can be effective to represent the self-reflection process as well.

The model assumed that general problem-solving is a state of transition of the WM influenced by five cognitive activities: “observation,” “rehearsal,” “evaluation,” “virtual application,” and “selection.” Observation involves carefully looking at the subject and generating the model as the product in the WM. Rehearsal involves keeping the product in the WM to support complicated cognitive operations. Evaluation involves making it possible to search for applicable operators from the knowledge base. The virtual application involves virtually executing an applicable operator in the knowledge base to generate an action list. Selection involves selecting an optimal operator from the results of the virtual application and generating a list of operators to actually apply (action list). When applying the generated action list, the WM’s products shifts to new products.

In the WM upper layer, metacognitive activities can be described as cognitive activities that observe and coordinate cognitive activities performed in the WM lower layer. There are two ways to generate products from this metacognitive

activity: reflection *in* action and reflection *on* action. The former involves coordinating the cognitive operation in the lower layer and observation thereof in parallel, and generating the observation results in the upper layer as a product. The latter involves observing the products (i.e., cognitive operation process to a product) in the lower layer and generating the process as a product in the upper layer.

Proposed model for problem solving

We attempted to model self-reflection based on the two-layer WM model. Our model focuses on the reflection on action. Previous studies suggest that the failure experience lets humans generate, transpose, and improve strategies [4, 5]. Chiken et al. [6] suggested that strategies are generated by knowledge construction from the failure experience. They also suggested that failure knowledge can be organized into six categories: event, background, process, cause, coping, and summary. In other words, the reflection on action process implies the acquisition of metacognitive knowledge by organizing the failure experience from these categories [7]. Above all, self-reflection is defined as "constructing a strategy by reflection on action through the construction of failure knowledge."

A conceptual model of self-reflection is shown in Figure 1. The model shows that 1) failure feedback triggers the construction of the failure knowledge. 2) To identify the cause product, trial and error of coping (through virtual application) and observation of the result are carried out. 3) As the cause is specified, the background, coping, and cause product are associated with each other. Finally, 4) the association is stored in long-term memory (LTM). The stored strategies in LTM can be easily accessed to adjust cognitive operations in the WM lower layer during the next problem resolution (i.e., reflection in action).

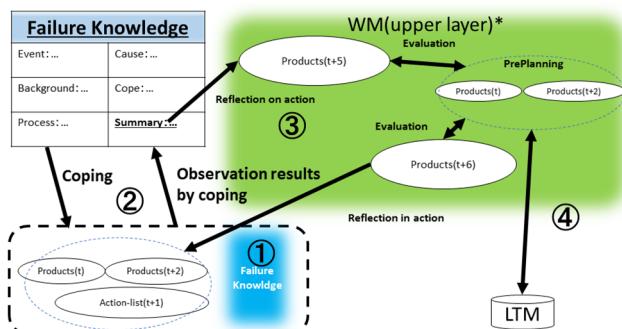


Figure 1. Conceptual model for self-reflection

SYSTEM IMPLEMENTATION

Food recommendation function

The food recommendation function performs cognitive operations in the WM lower layer in Kayashima's model. The problem-solving task of the system can be stated as reducing the number of food recommendation candidates using the cognitive operation module. Then, a food recommendation candidate is regarded as a product of this

system. For this system, we built an observation, virtual application, and selection modules.

The observation module observes the conditions of the food recommendation task. It receives context information as input from the user and then selects two contexts that the user might consider important. It's suggested that contextual information should work in recommender systems [8]. The virtual application module narrows down the recommendation candidates, which is the product, based on the observation results. We implemented three methods to determine the food candidates whose context values are 1) close to the user's input values, 2) high, and 3) low. This module generates three types of candidates. The selection module compares each output and then identifies the candidate as next product that meets the user's preference.

The database of meals used for the recommendations of this system was constructed based on a questionnaire survey. One hundred two culinary genres were selected from the most specific culinary genre registered in Tabelog (https://tabelog.com/cat_1st/, 2016/09/01). Fourteen subjects were asked to assign the corresponding context values when deciding what food to eat (e.g. "when you decide to eat pizza, your budget is...") using a 10-point Likert Scale. The context represented the budget, outside temperature he/she felt, number of people to eat with, time passed since he/she woke, and degree of hunger. These context values represent the conditions based on which the food will be chosen. Each food in database had the average context values.

"Self-reflection" function

The self-reflection function is represented by two modules: reflection module and conscious observation module. The reflection module generates and improves strategies based on failure knowledge. The failure knowledge construction begins as the user refuses a recommendation. Specifically, the food recommendation function is repeated. In this case, the combination of all the contexts (here called "virtual-context") is used (i.e., $5 \times 4 = 20$ foods were chosen), and all results are arranged in a list. When the list is displayed to the user, the user selects one food from the list. Then, the module determines the cause product from the selected food, in comparison to recommended food. The cause product can be referred to as the "context of interest" in recommendation or "narrowing down method." If the context of interest is the same as the context of recommended food, the narrowing down method that the system adapted is considered as the cause product of the failure experience.

The conscious observation module adjusts the meal recommendation function based on the strategies constructed in the reflection module. This module works whenever a similar situation as that of a recommendation failure occurs at the start of the recommendation. When the conscious observation module is activated, it displays to the user which part of the internal processing of the food recommendation by the system was changed. For example, the system said "I previously made a mistake in a similar situation. The recom-

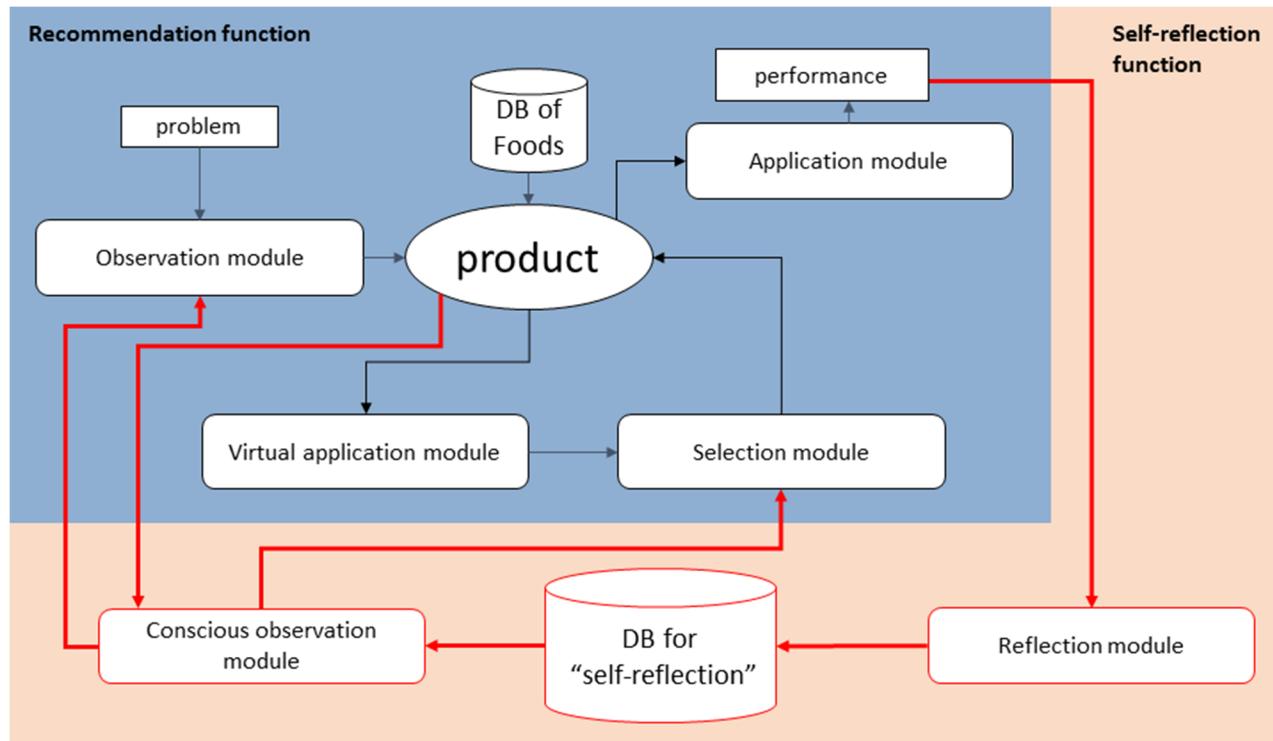


Figure 2. System diagram: The blue and orange part indicate the recommendation and self-reflection function, respectively.

mended food was yakisoba but you preferred yakiniku. *I should have taken into consideration the budget and the number of persons eating with you. Perhaps, the number of persons is important to you! Therefore, in this case, ...*"

EXPERIMENT 1

Purpose

The purpose of this experiment is to verify the usefulness of the reflection function and to collect the items recommended by the system for assessing the metacognitive model (ref. Section "Experiment 2").

Procedure

Fifteen subjects (college students, graduate students, and social workers; 10 males, 5 females) participated in the experiment to interact with the system. They were asked to determine their own 10 dietary situations with the given context and received recommendations (10 times for each participant). They decided whether or not to accept the recommendations in each trial. After the interaction, participants were asked to evaluate the degree of 1) satisfaction and 2) unexpectedness of each recommendation with a 10-point Likert scale. In addition, we defined the recommendation acceptance rate to assess the reflective system. We also constructed a general system and a random system to evaluate the verification of the self-reflection module. The general system removes the self-reflection function from the reflective system. On the other hand, the random system decides on all recommendations randomly from the database. Each system also displays the internal processing. For example, the general system presents recom-

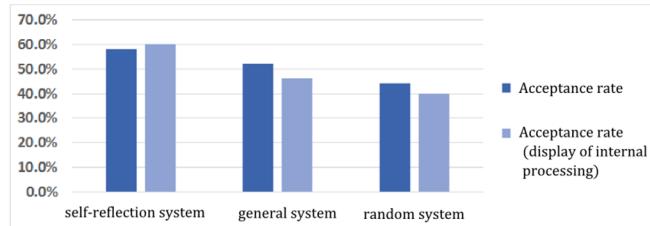


Figure 3. Acceptance rate of each system

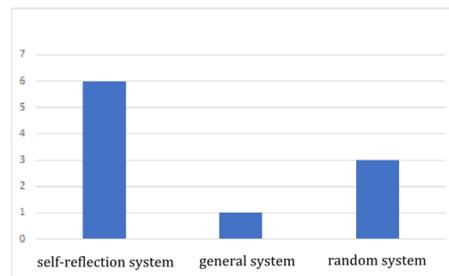


Figure 4. Number of the recommended items whose unexpectedness and satisfaction were evaluated more than 7

mendations such as, "... This time, I changed the recommendation strategy, that is, I recommend food that everyone, in this case, chooses. So, in this case,"

Results

The recommendation acceptance rate for each system is shown in Figure 3. The vertical and the horizontal axes represent the recommendation acceptance rates (%) and each system, respectively. The graphs indicate that the acceptance rate of the reflective system was higher than that of the other

systems. This tendency was enhanced when each system displayed the internal processing.

Figure 4 shows the number of recommendations whose satisfactory and unexpectedness were rated as 7 or higher for each system. The graphs indicate that the subjects who interacted with the reflection system tended to highly appreciate the unexpectedness and satisfaction provided by the system recommendations, compared with subjects who interacted with the other systems.

EXPERIMENT 2

Purpose

The purpose of Experiment 2 is to evaluate the validity of the self-reflection model. Because metacognitive activity cannot be observed, we compared the action list of the products (i.e., food candidates) of the system and humans.

Procedure

Three university students (2 males, 1 female) participated in the experiment and were asked to provide food recommendations 10 times to the person with the console (in a chat system). They were instructed to select the foods from the database two times, lining up the candidates and their contexts of interest. We compared the outcomes with the recommendation candidates and contexts of interest generated by the system in Experiment 1.

Results

The contexts of interest that participants reported in their self-reflection were different from that of our system. To assess the reflection module, we applied the participants' contexts of interest to the recommended module to extract the food candidates. Comparisons between the extracted food candidates and user's candidates show that the matching rates between some recommendation candidates on the list rose by as much as 40%. On the other hand, the matching rates for other recommendations decreased.

The characteristic of reflection behaviors presented as the result of an interview are as follows:

- In the second session, he/she seems to consider of his/her budget and number of persons to eat with. Therefore, this time, I recommended foods that were not too expensive and good for sharing with two persons.
- In a similar situation as the second session, I made slightly better recommendations. Hence, I recommended foods based on the degree of hunger. As he/she seems not to mention other context, the budget is taken care of anyway.

DISCUSSION

The participants who interacted with the self-reflection system tended to rate both unexpectedness and satisfaction higher than other recommender systems. The participants also accepted system recommendations, especially those of the self-reflection system. Therefore, our self-reflection system can satisfy their demands.

On the other hand, the results from the Experiment 2 indicate that the candidates generated by the system did not match those generated by participants, which implies that our self-reflection model did not follow the human self-reflection. This result suggests that the high acceptance rate and appreciation of unexpectedness and satisfaction should rely on anything other than the reflection function itself. Experiment 1 showed that the acceptance rate was higher when the system displayed the internal processing to users. Thus, it can be assumed that the display of the system influenced participant's high acceptance rate. As the system behaved as if it was engaged in self-reflection, participants could treat the system as a social being [9]. Such visual performance can help participants accept recommendations.

Another role played by the display of internal processing is encouraging appreciation for unexpectedness and satisfaction. In general, content-based recommender systems have difficulty in recommending the unexpected to users [10]. Our self-reflection system, however, provided such unexpected recommendations. The display contributed to participant's expectation that the system learned his/her preferences. Displaying the internal processing of the reflection system showed which processes and how the system changed based on the failure experience. From this point of view, participants predicted the internal processing model of the system (the rules the system acquired in accordance with their preference). Despite this, when the system recommended foods that were different from what they expected, the unexpectedness was enhanced. When the recommended food was appropriate for the situation they specified, they appreciated the system and were satisfied.

CONCLUSION

In this study, we proposed a cognitive model representing the self-reflection process and implemented it in a food recommender system. We conducted experiments to assess the system and the results indicated that the recommended foods were highly unexpected and satisfying for users. It was also suggested that displaying the internal processing of the system contributed to its high-performance rating from users. The display encouraged participants to believe that the system was learning in accordance with their preferences. On the other hand, the cognitive model was evaluated based on the consistency between food candidates selected by the system and the participants. The results showed that the selected foods were different from each other although both shared the self-reflection process in food recommendation, and that they modified the contexts of interest based on the failure experience.

In future work, we plan to address the following issues. The first is the experimental limitations. In the experiments, it was unclear whether situations participants assumed reflected actual situations. Furthermore, it is also important to study the reflection process in the learning context and consider the metacognitive model to explain the learner's reflection process.

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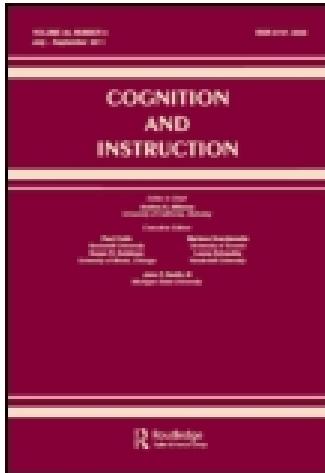
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Development of a Cognitive-Metacognitive Framework for Protocol Analysis of Mathematical Problem Solving in Small Groups

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A framework is presented that explicitly delineates the roles of metacognition and cognition within small-group heuristic problem solving in mathematics. This framework is used to describe the videotaped behaviors of 27 seventh-grade students of varying ability working in small groups to solve a mathematical problem. The results suggest the importance of metacognitive processes in mathematical problem solving in a small-group setting. A continuous interplay of cognitive and metacognitive behaviors appears to be necessary for successful problem solving and maximum student involvement. Within the groups, students returned several times to such problem-solving episodes as reading, understanding, exploring, analyzing, planning, implementing, and verifying. Stimulated-recall interviews held after completion of the task underscored an additional dimension of importance. Attitudes, particularly those of high-ability students, seemed to affect the interactions and the problem-solving behaviors of fellow group members. The framework shows promise of being a powerful tool for the future study of mathematical problem solving in a small-group setting.

Recently there has been a growing movement toward the use of small groups for mathematics instruction (Crabill, 1990; Johnson & Johnson, 1990; Lindquist, 1989; Noddings, 1989; Rosenbaum, Behounek, Brown, & Burcalow, 1989; Slavin, 1990). Research has shown that, under certain conditions, small-group approaches show positive effects on achievement in mathematics (Davidson, 1985; Davidson & Kroll, 1991). Support for small-group work now comes from the National Council of Teachers of Mathematics (1989) in its publication, *Curriculum*

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and Evaluation Standards for School Mathematics. The assumption is that through the use of small-group approaches the mathematical problem-solving abilities of students will be improved. Although there is optimism about the efficacy of small-group techniques, proponents acknowledge that little is known about the ways in which the activities used in these small-group approaches produce their positive effects (Bossert, 1988; Slavin, 1989–1990).

Over the last 2 decades, many researchers have studied problem solving in mathematics from a cognitive information-processing perspective. Recent summaries of studies investigating mathematical problem solving (Garofalo & Lester, 1985; Schoenfeld, 1987; Silver, 1987) suggest that a primary source of difficulty in problem solving may lie in students' inability to actively monitor and subsequently regulate the cognitive processes engaged in during problem solving. Small problem-solving groups provide natural settings for interpersonal monitoring and regulating of members' goal-directed behaviors. It may be that variables characteristic of these settings are responsible for the positive effects observed in small-group mathematics problem solving. In this exploratory study, we examine the cognitive processing that occurs as individuals engage in mathematical problem solving in small-group settings. Through this investigation, we hope to learn more about how levels of cognitive processes interact and contribute to the successful outcomes of problem solving within small groups.

To examine the interactions between two levels of cognitive processes (i.e., cognitive and metacognitive) observed in the problem-solving behaviors of students working in small groups on mathematics problems, we synthesized a framework for protocol analysis. The procedure has been used to analyze videotapes of students engaged in mathematical problem solving in small-group settings. The framework is derived from research on mathematical problem solving and on cognitive processes discussed in the following three sections.

MATHEMATICAL PROBLEM SOLVING

In mathematics, Polya's (1945) conception of mathematical problem solving as a four-phase heuristic process (understanding, planning, carrying out the plan, and looking back) has served as a standard for investigating problem-solving competence. More recently, Schoenfeld (1983) devised a model for analyzing problem-solving moves that was derived from Polya's. Schoenfeld's model incorporated, within Polya's structure, findings from research on problem solving by information-processing theorists. The model described mathematical problem solving in five episodes: reading, analysis, exploration, planning/implementation, and verification. Garofalo and Lester (1985) built on Polya's and Schoenfeld's structures by developing a framework for analyzing metacognitive aspects of performance on a wider range of mathematical tasks. The four broad component processes—orientation, organization, execution, and verification—are related to

Polya's four phases but are more broadly defined. The four components incorporate Schoenfeld's categories of reading and analysis taken together, planning, implementation, and verification, respectively. Exploration was not specified in the Garofalo and Lester framework. Although Garofalo and Lester indicated the distinctive metacognitive behaviors that may be associated with each category, more research is needed to analyze the specific cognitive processes inherent in mathematical problem solving.

Furthermore, in the application of his framework, Schoenfeld discovered that expert mathematicians returned several times to different heuristic episodes. For example, in one case, an expert engaged in the following sequence of heuristics: read, analyze, plan/implement, verify, analyze, explore, plan/implement, verify. In contrast, the sequence of heuristics for a novice problem solver was just read and explore. More research is needed to examine the sequence of heuristic episodes characteristic of novice problem solvers working in small groups.

COGNITIVE PROCESSES

Current studies of cognitive development focus on cognitive processes as well as on the mechanisms by which development in the processes occurs. Prominent in research on cognitive mechanisms have been strategy selection (e.g., in the solution of computational problems; see Siegler, 1988; Siegler & Shrager, 1984), processing efficiency (e.g., Kail, 1986; Sternberg, 1977), and social scaffolding (e.g., reciprocal teaching; see Palincsar, 1986; Palincsar & Brown, 1984).

Regarding cognitive processes, one lively area of research has focused on the knowledge, monitoring, evaluation, and overseeing that individuals use during any problem-solving endeavor. The term commonly used in the psychological literature for these cognitive processes is *metacognition* (e.g., Brown, 1978; Brown, Bransford, Ferrara, & Campione, 1983; Flavell, 1981; Jacobs & Paris, 1987). For example, Flavell (1981) defined *metacognition* as "knowledge or cognition that takes as its object or regulates any aspect of cognitive endeavor. Its name derives from this 'cognition about cognition' quality" (p. 37). The definition implies that metacognition includes reflection on cognitive activities as well as decisions to modify these activities at any time or place during a given cognitive enterprise. Flavell draws our attention to the dual nature of cognitive processes deployed during any given cognitive enterprise when he stated, "We develop cognitive actions or strategies for *making* cognitive progress and we also develop cognitive actions or strategies for *monitoring* cognitive progress. The two might be thought of as cognitive strategies and metacognitive strategies" (p. 53).

COGNITIVE PROCESSES IN MATHEMATICAL PROBLEM SOLVING

In his framework, Schoenfeld (1983) devised a scheme of parsing protocols into episodes and executive decision points. The executive decision points served as the mechanisms by which the problem-solving process was kept on track. Although his framework focused on the points at which metacognitive decisions may be considered and on their importance in the problem-solving process, in the analyses of protocols, Schoenfeld did not specify the cognitive levels of the episodes themselves.

To examine the problem-solving behaviors and cognitive processes of individuals as they work in small groups, we developed a framework that synthesizes the research on mathematical problem solving with that of cognitive theorists.

DESCRIPTION AND DEVELOPMENT OF FRAMEWORK

The framework for the protocol analysis of problem solving in mathematics developed for this study was designed to differentiate explicitly between cognitive and metacognitive problem-solving behaviors observed within the different episodes of problem solving. Our framework attempts to show a synthesis of the problem-solving steps identified in mathematical research by Garofalo and Lester, Polya, and Schoenfeld, and of cognitive and metacognitive levels of problem-solving behaviors studied within cognitive psychology, in particular, by Flavell (1981).

Schoenfeld's (1985b) framework was used as a foundation in our development. His framework partitioned a problem-solving protocol into "macroscopic chunks of consistent behavior called episodes. An episode is a period of time during which an individual or a problem-solving group is engaged in one large task" (p. 292). The episodes were categorized as *read*, *analyze*, *explore*, *plan/implement*, and *verify*. Through the determination that decisions at the control level would be those that affected the allocation or utilization of problem-solving resources, Schoenfeld allowed for junctures between episodes where these decisions would be most likely to occur. Furthermore, he made specific indications when overt signs of management activity occurred. His framework focused mainly on decision-making behaviors, specifically on statements made about the problem-solving process, at the executive level. A limitation of his framework, Schoenfeld admitted, was that he did not identify statements made about the problem (the more "local" indications of metacognitive behavior). He claimed that, as a result, he was unable to address the important role that consistent monitoring and evaluation of solutions play in the problem-solving process (1985b, p. 293).

Schoenfeld's framework was taken as a starting point; changes were then made to serve the purposes of the present investigation: to delineate explicitly the type and level of cognitive processes individuals use as they work with others in a small-group setting and to understand the mechanisms by which these processes facilitate problem solving. Following Schoenfeld, episodes were used to categorize the behaviors of the individual students within the group. Through the context of the verbal interactions that occurred within the small groups, however, it became clear that several modifications to Schoenfeld's episodes were needed. First, the episode of plan/implement was separated into two distinct episodes. This seemed advisable because the two episodes did not always occur sequentially in the small-group setting. In fact, quite often, a student proposed a plan that was immediately rejected by the other group members. In such cases, no implementation occurred. Second, it became apparent that we had to expand the episodic categories for the coding of student behaviors in groups to include *understanding the problem* and *watching and listening*. The frequent comments students made regarding the conditions of the problem, recognized by Polya as so important in the problem-solving process, served as our reason for including understanding the problem as a distinct episode. Furthermore, the verbal interaction that took place within the small group implied that at certain times students were watching and listening to one another.

Each of the eight problem-solving episodes (read, understand, analyze, explore, plan, implement, verify, watch and listen) was categorized as cognitive or metacognitive. Conceptually, one can distinguish the dual nature of cognitive processing, but operationally the distinction is often blurred. For example, cognition is implicit in any metacognitive activity, and metacognition may be present during a cognitive act, although perhaps not apparent. For this reason, none of the episodes was categorized as purely cognitive or purely metacognitive. The distinction was based on the predominant process observed.

Our working distinction of cognition and metacognition was similar to Garofalo and Lester's (1985, p. 164) description, "Cognition is involved in doing, whereas metacognition is involved in choosing and planning what to do and monitoring what is being done." Metacognitive behaviors can be exhibited by statements made about the problem or statements made about the problem-solving process. Cognitive behaviors can be exhibited by verbal or nonverbal actions that indicate actual processing of information. This distinction between cognitive and metacognitive actions corresponds to those of Flavell (1981) as well. See Table 1 for an outline of the categorization of episodes. A rationale for these categorizations follows.

Episodes of analyzing and planning are, by their very natures, predominantly metacognitive behaviors. Schoenfeld (1985b) stated that:

In analysis an attempt is made to fully understand a problem, to select an appropriate perspective and reformulate the problem in those terms, and to introduce for

TABLE 1
Framework Episodes Classified by Predominant Cognitive Level

<i>Episode</i>	<i>Predominant Cognitive Level</i>
Read	Cognitive
Understand	Metacognitive
Analyze	Metacognitive
Explore	Cognitive and metacognitive
Plan	Metacognitive
Implement	Cognitive and metacognitive
Verify	Cognitive and metacognitive
Watch and listen ^a	

^aLevel not assigned.

consideration whatever principles or mechanisms might be appropriate. The problem may be simplified or reformulated. (p. 298)

Any statements revealing such thought processes would necessarily be statements made about the problem or about the problem-solving process. Similarly, episodes of planning would be evidenced by statements made about how to proceed in the problem-solving process. Episodes of understanding the problem were categorized as predominantly metacognitive, because this category was assigned only when students made comments that reflected attempts to clarify the meaning of the problem. That is, if a student was making a comment about the meaning of a problem, he or she was also making a comment about the problem. Although it is true that some of the things one does to understand a problem are cognitive, in a coding scheme that relies on the verbal comments of students, it is impossible to decipher the understanding that is being derived during the actual doing of the problem. Behaviors coded as reading were categorized as predominantly cognitive, because they exemplify instances of doing. Behaviors coded as exploring, implementing, and verifying were sometimes categorized as cognitive and sometimes as metacognitive. As Schoenfeld (1987) documented, exploration at the cognitive level alone often results in unchecked "wild goose chases" (p. 210). When exploration is guided by the monitoring of either oneself or one's groupmate, that behavior can be categorized as exploration with monitoring or exploration with metacognition. As a consequence of such monitoring, either self or group regulation of the exploration process can occur, thereby keeping the exploration controlled and focused. The same analysis applies for implementation and verification, which can occur with or without monitoring and regulation. The lack of verbalization during episodes categorized as watching and listening made it impossible to infer a level of cognition. Therefore, these episodes were not categorized as either cognitive or metacognitive. Nonetheless, this last category may still be an important dimension in the process of problem

solving in a small-group setting. See the Appendix for a detailed description of the framework.

Figure 1 illustrates the variety of sequences of behavior that could occur during the problem-solving session. Specific examples of the protocol analysis follow the explanation of the mathematical problem.

Unlike previous models, this framework delineates the type and level of processes used as individuals solve mathematical problems in small-group settings. It thereby enables the researcher to examine the role of cognition and metacognition within the heuristic framework of mathematical problem solving in a small-group setting.

METHOD

Subjects

The subjects for this study were 27 seventh-grade students (11 girls, 16 boys) who attended an urban public middle school in the borough of Queens, New York City. The students were selected from three average-ability mathematics classes

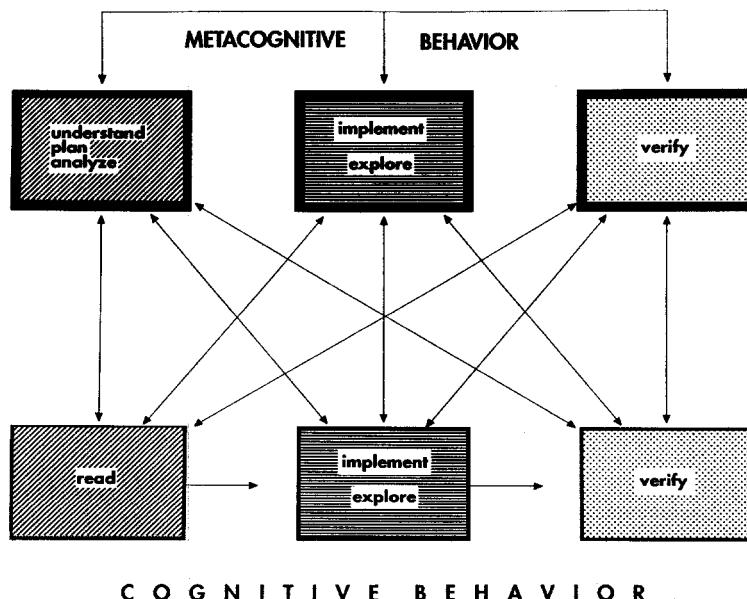


FIGURE 1 A cognitive-metacognitive model. Phases of the problem-solving enterprise.

TABLE 2
Mathematics Problem-Solving Ability:
Percentile Scores on the Metropolitan Achievement Test

Students	Group					
	1A	1B	2A	2B	3A	3B
Quartile (Q)						
Q ₄	94	97	99	97	99	94
	82	86	82	86		
	82	77		86		
Q ₃	69		73	59	69	63
	50			55	59	55
					50	
Q ₂			33		25	25
Q ₁		18				
Range	44	79	66	42	74	69

taught by two teachers. Only 1 of these students had prior experience in a problem-solving workshop. One week before the study, teachers divided their classes into groups of 4 or 5 students of heterogeneous ability in mathematics. The purpose of this preliminary group experience was to make the students familiar with their group members and the process of group work. In each of the three classes, two groups of students were randomly selected for observation and videotaping, for a total of six groups: Groups 1A, 1B, 2A, 2B, 3A, and 3B. Each group was heterogeneous in mathematical problem-solving ability as measured by the problem-solving section of the Metropolitan Achievement Test. Table 2 lists the students' national percentile scores. The scores are listed according to the groups to which the students belonged and the appropriate quartile in which their scores fell. The groups having the same number (e.g., 1A and 1B) were members of the same class. Each group contained students differing in ability, sex, race, and ethnic background.

Of all six groups, Groups 1A and 2B were the only two whose members all scored above the 50th percentile. In general, these groups were most homogeneous and higher in ability.

Groups 3A and 3B were similar in that they each had only one student who scored in the upper quartile. In fact, each of these students was at the high end of the upper quartile. The students next in ability were in the middle of the third quartile. These groups each contained members at the lowest end of the second quartile. In general, these two groups contained a higher percentage of lower ability students than the other groups, and they had the widest range between the highest ability student and the second highest ability student.

Procedure

Instruments

Students' mathematical problem-solving ability was estimated from their most recent score on the Metropolitan Achievement Test (intermediate form). The test is administered annually in all middle schools. Scores on each student's school record card are recorded as percentiles. Informal interviews were used to obtain mathematics teachers' perceptions of each sample member's ability, attitude, and classroom behavior. Mathematics grades from teachers were a second index of achievement.

Problem Solving in Small Groups

As the students entered the class on the day of the study, they were instructed by the teacher to sit with their groups. They were asked to solve a mathematical problem by working with their group members.

The students were not given a time limit for working on the problem. The teacher called the class together when it was clear that most of the groups had solved the problem and that the few that had not solved the problem seemed unable to proceed further. The problem-solving session lasted between 15 and 20 min.

Videotape of Group Work

In each of the three classes, the investigator (first author) and a research assistant videotaped the two randomly selected groups for the full time they worked on the problem. The videotape was used to provide a permanent record for the coding of problem-solving behaviors. Each of the videotapes was transcribed.

Stimulated-Recall Interview

Within 1 week of the videotaping session, each student participated in a private, stimulated-recall interview as he or she watched the videotape of himself or herself working in the group at six specific times: (a) before his or her group was given the problem, (b) when his or her group was given the problem, (c) when the child began to work on the problem in his or her group, (d) when he or she was deeply involved in working on the problem in his or her group, (e) when the child thought that his or her group had arrived at the solution, and (f) after his or her group had finished working on the problem. These episodes were located by the investigator who viewed each tape and indicated the number on the VCR counter that corresponded to each episode. Students were asked to recall their thoughts during these times in the problem-solving session. The investigator and the research assistant conducted the interviews, which were audiotaped and transcribed.

These interviews provided opportunities to learn about (a) attitudes regarding the task, (b) contributions and participations as group members, and (c) awareness of the problem-solving episodes in which they or their group was engaged (an aspect of metacognition not easily identified through observance of behavior alone).

Coding of Problem-Solving Behaviors

To reach consensus on the categories that best described the observable behaviors, the authors and a research assistant randomly selected one videotape to be used as a pilot tape. The coders worked on the application of the framework until there was strong agreement on how the categories were to be defined and what behaviors were representative of these categories. The interrater reliabilities were high: 93% agreement between the two authors and 91% agreement between the research assistant and one of the authors. In addition, during the actual coding process, if any one of the observers was doubtful about how to categorize a certain behavior, all three observers watched the episode in question and agreed on the appropriate category.

The six videotaped groups consisted of either four or five students. The authors and a research assistant viewed the videotape of each group as it worked on solving the problem. Each viewer watched the behavior of one or two students. The tape was viewed in 1-min intervals, after which each viewer coded the heuristic episode and the cognitive level that best represented the behavior of the student(s) she was observing. Students often exhibited several behaviors during the 1-min time interval. Each behavior was indicated in sequence.

Group Problem-Solving Task

The students were asked to solve the following problem: "A banker must make change of one dollar using 50 coins. She must use at least one quarter, one dime, one nickel, and one penny. How many of each coin must she use to do this?"

The banking problem was selected for several reasons. First, because it cannot be solved using a strict algorithmic procedure, it lends itself to a variety of less structured problem-solving approaches. Second, because students are familiar with money, it was likely that they would understand and be interested in solving the problem. Third, the teachers judged it as an appropriate problem for the ability level of their students.

Before describing the problem-solving behaviors of the students and giving actual protocol examples, we examine the banking problem in light of the proposed framework. We present an outline of several approaches that could be used (many of which the students did use) to solve this problem. These approaches are categorized by episodes—although the episodes are numbered, they are not assumed to be sequential in their occurrence—and cognitive levels as follows:

Episode 1: Reading the problem (cognitive). The student must read or listen to someone else read the problem.

Episode 2: Understanding the problem (metacognitive). The student must understand that there are three conditions that must be met when solving this problem.

1. There must be a total of 50 coins.
2. The value of the coins must be one dollar.
3. There must be at least one quarter, one dime, one nickel, and one penny.

Episode 3: Analyzing the problem (metacognitive). If the students attempt to analyze the problem, there are many ways it can be done. For example:

1. The problem can be reformulated by using the condition that one of each type of coin must be used. That is, four coins (one quarter, one dime, one nickel, and one penny) have the value $25 + 10 + 5 + 1$ or 41 cents. This reduces the old problem to a new one having one less condition. That is, now one must find any 46 coins that total 59 cents. No longer is there a restriction about the type of coins that must be used.
2. Because quarters, dimes, and nickels are all multiples of five, their sums, in any combination, will be a multiple of five. Because the sum must be 100, and 100 is a multiple of five, the number of pennies used must also be a multiple of five.
3. For fifty coins to be worth only \$1.00, most of the coins selected will have to be pennies.
4. Not many quarters can be used, because four quarters are equivalent to one dollar and 50 coins must be used.

Episode 4: Planning (metacognitive). If the students attempt to plan an approach for solving the problem, there are many ways it can be done. For example:

1. Divide \$1.00 into four quarters. Leave one quarter, and keep breaking down the remaining quarters until there are 50 coins.
2. Make a chart using headings of quarter, dime, nickel, and penny. Start with one coin of each type, and then continue adding coins until there are 50 coins totaling \$1.00.
3. Start with 50 pennies, and then exchange the pennies for the other coins.
4. Manipulate actual coins to get an idea of how to solve the problem.

Episode 5: Exploring (cognitive and metacognitive). This problem lends itself to a guess-and-test problem-solving approach. This is a form of exploration. If a student is making guesses, testing the guesses, and then making new guesses based on the results of the old ones, he or she is monitoring and regulating the exploration (metacognitive). This, in fact, is an effective technique for solving this particular problem. If, however, the student is merely making

a series of random guesses, the student is embarking on an unmonitored exploration (cognitive alone) that is unlikely to result in a solution.

Episode 6: Implementing (cognitive and metacognitive). If a student has devised a plan for solving the problem, he or she is likely to try to implement the plan. If the student does this systematically by monitoring and regulating the implementation (metacognitive), the student is likely to find that the plan either was good and has led him or her toward a solution or was not good and has led him or her to relinquish the implementation and try to devise another plan. If the implementation is not monitored (cognitive alone), however, the student may get buried in the implementation of a poor plan that is unlikely to lead to a solution.

Episode 7: Verifying (cognitive and metacognitive). For an effective verification to take place, the student must be able to take his or her final solution and check that the number of coins is 50, that the total value of the coins is \$1.00, and that one of each type of coin is used. This process entails the ability to add numbers (cognitive) and the ability to monitor the results to check that they meet the conditions of the problem (metacognitive).

Episode 8: Watching and listening (uncategorized). For students to exchange ideas that may facilitate the problem-solving process, they must be willing and able to listen and watch each other.

Protocol Examples

We give several examples of group discussion protocols during different phases of the problem-solving process. The coding of each member's behaviors is given as well. Because the coding was based on the behaviors viewed as well as heard, an overview scenario of the behaviors of the students within the groups is also given. The coding decisions were made on the basis of the overriding behaviors of the students rather than on the basis of each individual statement made.

This first protocol presents the behaviors and the statements of four students (R,O,S,K) in Group 1B during the beginning segment of their problem-solving session (all four students silently read the problem from the blackboard). Student R took the lead in analyzing and devising plans for solving the problem. He was the only one in the group, however, who did practically no writing. All he did was talk about the problem. The other three students did some implementing of his plan while they seemed to be struggling to understand the requirements of the problem. It seemed that they were attempting to solve the problem using Student R's lead before they really understood what the problem asked them to do (evidenced by the statements they made). The protocol follows:

1. S: How many dollars?
2. R: One dollar. We have to use at least one of each to make one dollar. Let's try to get rid of the biggest coins first.

3. S: (Shakes head in agreement and begins to write.)
4. R: Let's get rid of the dimes too so we can get rid of the biggest coins first.
5. K: The dimes?
6. R: Yeah, so you have 35 cents.
7. K: Work with the nickels first.
8. R: No, 'cause we have to use the quarters, dimes, and the nickels.
9. O: Okay, one quarter—(as she writes).
10. R: We have to use a quarter and a dime, which adds up to 35 cents.
We have 35 cents already.
11. K: One quarter, one dime (as he writes).
12. O: You know it has to equal one dollar.
13. R: We used two coins already. Let's use five pennies.
14. K: A nickel—
15. R: That's 40 cents.
16. S: Use two quarters.
17. R: No, let's use two of the biggest ones—a quarter and a dime.
That's 35 cents.
18. S: We should use pennies then.
19. K: There has to be pennies?
20. S: There has to be 50 coins.
21. K: Fifty coins? One dollar? Okay.
(They all start writing.)

Student R. In Statement 2, this student clarifies to himself and others the conditions of the problem (understanding). By deciding to "try to get rid of the biggest coins first," he has immediately launched into a plan. Statements 4, 6, 8, and 10 show that he is sticking to his plan and, in his head, is implementing (cognitive) his plan. By stating that he has accumulated 35 cents (Statements 6 and 10) and by declaring that they have used two coins already (Statement 13), he demonstrates that he is keeping track of or monitoring his implementation (implementing: metacognitive). His suggestion to use five pennies (Statement 13) shows that he is about to go off track from his original plan to use the "biggest coins" first. However, he is kept in line by Student K, who interprets his "five pennies" as a nickel (Statement 14). When Student S suggests the use of two quarters, he rejects it by emphasizing his original plan. Within this segment, Student R's behaviors were coded as follows: reading, understanding, planning, implementing (cognitive and metacognitive).

Student S. In her very first remark in Statement 1, this student shows that she is trying to understand the requirements of the problem (understanding). She shakes her head in agreement to Student R's plan, and, from her subsequent writing, one would assume that she is implementing Student R's plan (implement-

ing: cognitive). Having used the three largest coins, she suggests the use of two quarters (Statement 16). There is no obvious plan at work at this point, and this suggestion seems to mark the beginning of exploring (metacognitive followed by cognitive) of the problem. Student R reminds her of his plan, and it appears from Statement 18 that she, having used all of the largest coins, is ready to use the pennies. In Statement 20, she is again trying to clarify the conditions of the problem for herself and her group. Within this segment, Student S's behaviors were coded as follows: reading, understanding, implementing (cognitive), exploring (metacognitive and cognitive).

Student K. In Statement 5, this student seems to be trying to understand Student R's suggested plan. He then contributes his own plan, which is immediately rejected by Student R (Statement 7). Although his idea of working with the nickels first takes the form of a plan, the fact that it is at such a local level (within Student R's plan), with no apparent rationale behind it, suggests that the appropriate coding is exploring (metacognitive). In Statement 14, he interprets Student R's suggestion to use five pennies as meaning to use one nickel. This monitoring of Student R's implementation helped the group stick to the original plan (implementation: metacognitive). When he asks if pennies must be used (Statement 19), the student shows that he did not yet fully understand the conditions of the problem. During this segment, the behaviors of Student K were coded as follows: reading, exploring (cognitive), implementing (metacognitive), understanding.

Student O. This student was mostly engaged in listening and writing. She only made two comments – once in Statement 9, when she was following Student R's directions, and then again in Statement 12, when she was trying to clarify the conditions of the problem to herself. Within this segment, the behaviors of Student O were coded as follows: reading, watching and listening, implementing (cognitive), understanding.

The second protocol presents the behaviors and the statements of four students (C, D, S, W), referred to as Group 3A, during the middle segment of their problem-solving session. The students have just reached the conclusion that they can reformulate the initial problem by first meeting the conditions of using one of each coin. The students have been working cooperatively, and each student has been engaged in the process of trying to solve the problem. We join them as they try to make sense of where they stand by exploring the revised problem.

1. W: Wait! Wait! We already have 41 cents with 4 coins.
2. C: How much more do we need?
3. W: Now we need 46 coins.
4. S: 46 coins and we need, um –
5. C: 59?
6. W: 59 cents.

7. S: Yeah.
8. D: So use all the pennies.
9. W: Forty-what coins? Forty-six.
10. C: Forty-six coins.
11. W: 59 and 46, what is it?
12. S: No, but you're getting confused 'cause this is the number of cents and this is the number of amount of coins.
13. W: No, but I mean what if we use 46 pennies?
14. D: It's a dollar five.
15. C: Yeah, but we have to use nickels and pennies.
16. D: Yeah.
17. W: All right.
18. S: Maybe we could use 5 nickels and then 41 pennies.
19. W: Try it.
20. S: So 5 nickels is 25 plus 41.
21. C: (Working on his own) Sixty-six again! We already did that.
Forty-one plus twenty-five.

Student W. In Statements 1, 3, 6, 9, and 11, this student engages in an assessment of the status of the problem solution. He is figuring out how many coins and how many cents he must have after he already has used 41 cents with 4 different coins. Because we are joining him in the middle of an exploration, this behavior was coded as exploring (metacognitive). In Statement 11, he reveals his confusion of coins and monetary value and, although he does not openly admit it, he is straightened out by student S's comment. In Statements 13, 17, and 19, he makes suggestions and gives encouragement for further exploration of the problem. His suggestion to use 46 pennies was exploratory. Within this segment, the behaviors of Student W were coded as exploring (metacognitive).

Student S. This student's clarifying comment in Statement 12 exemplifies the type of higher level statement that can keep a group's effort on track. In effect, she has monitored the exploration of Student W (exploring: metacognitive). From Statements 18 and 20, it is clear that she has joined in the exploratory efforts of the group by both giving suggestions and making her own calculations (exploring: cognitive and metacognitive). During this segment, the behaviors of Student S were coded as exploring (cognitive and metacognitive).

Student C. During the beginning of this segment, this student was listening to Student W. Afterward, in Statements 2, 5, and 10, he interacted with Student W in exploring the problem. Student C appears to finish the thoughts and sentences that Student W begins (exploring: metacognitive). Although the ideas are not initially his, he adds to the clarification of the issues by helping Student W along. In Statement 15, he reminds the group of the conditions of the problem

(although he was incorrect by recalling the need to use both nickels and pennies, because by then the students had already used one of each coin). Whether or not his statement was valid, he was engaging in efforts to clarify the conditions of the problem; thus, his statement was coded as understanding. Finally, in Statement 21, he joins the group in exploring the problem both cognitively (by working on Student S's suggestion) and metacognitively (by recognizing that the result was incorrect and, in fact, one that they had already reached). Within this segment, the behaviors of Student C were coded as follows: watching and listening, understanding, exploring (metacognitive and cognitive).

Student D. During the beginning of this segment, this student was listening to the remarks made by the other group members. In Statement 8, he suggested using "all the pennies." Although his suggestion sounded somewhat arbitrary and was, therefore, coded as exploring (metacognitive) rather than as planning, it had the potential to set the group on the right track. However, instead of adding the 46 pennies to the 41 cents that were already set aside, he added the 46 pennies to the 59 cents that was the sum to be sought (Statement 14). This gave him a total of "a dollar five," with which he could not work. Unfortunately, nobody in the group noticed his error. Within this segment, the behaviors of Student D were coded as follows: watching and listening, exploring (metacognitive and cognitive).

The third protocol presents the behaviors and the statements of four students (D, J, P, T), referred to as Group 2A, and the teacher (G) during the last segment of their problem-solving session. In this group, Student J appeared to be the prime problem solver. Because she did not have a pen or pencil, she dictated her ideas to Student P, who struggled to keep up with her suggestions. Student D busily worked on his own explorations, whereas Student T, the least involved, intermittently reminded fellow group members of the conditions of the problem. We join these students after their initial analysis that they need to find 59 cents using 46 coins. They have been lost in exploration for approximately 7 min.

1. J: Listen, if we have to use one of each, already we have 41 cents. We have 4 coins right? That means we need how many more coins? We need 46 more coins. So 46 coins and 41 cents. We have to break it down into nickels and pennies and everything else.
2. T: Pennies. Use all pennies.
3. J: Yeah, but that's too many. If we use all pennies, we wouldn't have enough.
4. D: It all depends on the pennies [Student T]. I bet you it all depends on the pennies.
5. T: I know. (Student P is holding the pencil, not knowing what to write. Student S does not have a pencil or paper.)
6. J: I'm confused now. (Thinks awhile and then instructs Student P) Put 40 pennies down.

7. P: 40 pennies?
8. J: Yeah—put 40 pennies. Now put one quarter, one dime. So that's 25, 35, (45, 55, 65 to herself) 75 cents. So we need 7 more coins.

(P is writing and trying to calculate to catch up with J's ideas.)

9. J: Use 45.
10. D: (Interrupting J) I got it! I got it! Look, 20 pennies, 1 nickel, 5 dimes, and 25 cents equals a dollar.
11. P: That's only . . . (counting up the number of coins)—
12. T: You've got to use 50 coins.
13. D: Oh, I was so close.
14. K: (Getting back to work with P) All right, so how much do we have here now? We have 44 coins. You got 80 cents. (Calculating to herself) That's 46. We need 4 more coins: 42, 43, 44, 45, 46. No, two. (P looks confused) Add another dime (calculating to herself).
15. D: It would have been easier if they told us how much money do we give the banker.
16. J: Put another dime in.

(T reads the problem to D.)

17. J: (Calculating what P has written) That's 50 coins. Look so that's . . . (calculating to herself) I got it! I got it! Look, look, 45 pennies, 2 nickels, 2 dimes, and a quarter. That's it.
18. D: Yea [Student J]!
19. T: Yes [Student J]!
20. D: Champion! We have it. Yea!
21. P: (Still looking bewildered, trying to figure out what he has written on the paper.)
22. J: (To P) What are you doing? Two nickels. . . .
23. P: Ten cents is two nickels.

(The teacher walks by.)

24. D: Miss G, we think we got it.
25. J: (To Miss G) Forty-five pennies, 2 nickels, 2 dimes, and 1 quarter.
26. G: But how come [Student P] is saying no?
27. P: Four, five, six . . . (Talking out loud as he still tries to figure it out.)
28. D: (To P) Carry the one.
29. P: I did.
30. J: (Pointing to the numbers on P's paper) 45, 55, 65, 75–75 and one quarter is a dollar. We got it.

Student J. In Statement 1, this student is clearly analyzing the problem. Student T comes up with a suggestion that she rebuffs in Statement 3. The student's suggestion was done at the local level and could, therefore, be categorized as a suggestion for exploration. Student J's statement would thus be categorized as monitoring the exploration (exploring: metacognitive). In Statement 6, Student J launches her own exploration by telling Student P to "put 40 pennies down." She calculates and monitors her own suggestion in Statement 8 (exploring: metacognitive and cognitive). By Statement 9, she hits on the correct number of pennies but is interrupted by Student D. When she returns to her ideas in Statement 14, she forgets about her suggestion of using 45 pennies and evaluates the status of the problem with her original idea of using 40 pennies. From this point on, she does most of the work in her head (Student P cannot keep up with her pace). Finally, in Statement 17, she checks her own exploration and discovers that she has solved the problem. She states her answer to the teacher and impatiently tries to help Student P verify the solution. Her final verification is in Statement 30. Her declaration, "We got it," shows that she has verified and checked the solution against the conditions of the problem. She has not merely added numbers but has also monitored the meaning of those numbers. This is an example of verifying at the metacognitive level. Within this segment, the behaviors of Student J were coded as follows: analyzing, exploring (metacognitive and cognitive), verifying (metacognitive and cognitive).

Student P. At this point in the problem-solving session, this student was acting as a secretary. Primarily, he was taking instructions from Student J. At one point, he took a moment to monitor Student D's incorrect proclamation that he had solved the problem (Statement 11). Because Student D's solution came out of extensive exploration, Student P's comment would be categorized as exploring (metacognitive). Because most of his behaviors entailed writing numbers that he did not seem to understand fully, his behavior was coded as exploring (cognitive). At the end of the session, Student P was attempting to verify Student J's solution. This was only at the cognitive level, however, because he still did not seem to have a grip on the problem. Within this segment, the behaviors of Student P were coded as exploring (metacognitive and cognitive).

Student D. This student picked up on Student T's suggestion that the number of pennies used would be very important (Statement 4). This was coded as analyzing. He strayed from the group and went off into his own calculations until he declared his solution in Statement 10. His calculations, compounded by his monitoring of the calculations that led him to believe that he had solved the problem, served as a rationale for coding these behaviors as exploring (metacognitive and cognitive). Students P and T alerted him to the fact that he had satisfied only some of the conditions of the problem. He understood their point and, in Statement 15, stated his wishes for a change in the wording of the problem.

At the end, he cheered for Student J. He watched the calculations that Student P was making as he tried to verify Student J's solution. During this segment, the behaviors of Student D were coded as analyzing, exploring (metacognitive and cognitive), watching and listening.

Student T. This student did not do any calculations during the entire problem-solving session. He spent most of his time watching and listening to the other students. He gave an important suggestion in Statement 2 to "use all pennies." Because this suggestion came at the local level, it was categorized as exploring (metacognitive). After that, his only other statement was to remind Student D of the conditions of the problem. Within this segment, the behaviors of Student T were coded as watching and listening, exploring (metacognitive), understanding.

RESULTS

Results of Problem Solving in Small Groups

The coding for each of the six groups observed was done on charts such as those shown in Figures 2, 3, and 4. The behavior of each student was categorized in two ways: by episode and by cognitive level. The episode or type of problem-solving behavior in which the student was engaged (read, understand, analyze, explore, plan, implement, verify, watch and listen) was recorded in the appropriate row. An asterisk indicates metacognitive behaviors. All other behaviors, except those categorized as watch and listen, were considered to be cognitive. Those categorized as watch and listen were not assigned a cognitive level.

Students' behaviors were coded in 1-min intervals. The time intervals are listed along the bottoms of Figures 2 through 4. Behaviors (episodes) are listed on the vertical axis and are displayed throughout the charts. Students are distinguished from one another by their first initial. For example, in Figure 3, during the first minute, Student C first read the problem, then tried to understand the problem, and then began to do some exploratory work. During Minute 2, Student C watched and listened to what the other students were doing and saying and then resumed exploratory work. Charting each student's behavior in this way yields a picture of each individual's behavior. As an added outcome, a picture of the group's behavior as a whole seems to emerge. (The protocol example of Group 3A can be located in Figure 3 during approximately the fifth to seventh minutes.)

Each figure contains a small table summarizing the behaviors of each student in the group. These behaviors are categorized as metacognitive, cognitive, and watch and listen. By counting the number of metacognitive behaviors coded for one student and dividing it by the total number of behaviors coded in the group, a profile can be obtained of each group member's metacognitive contributions

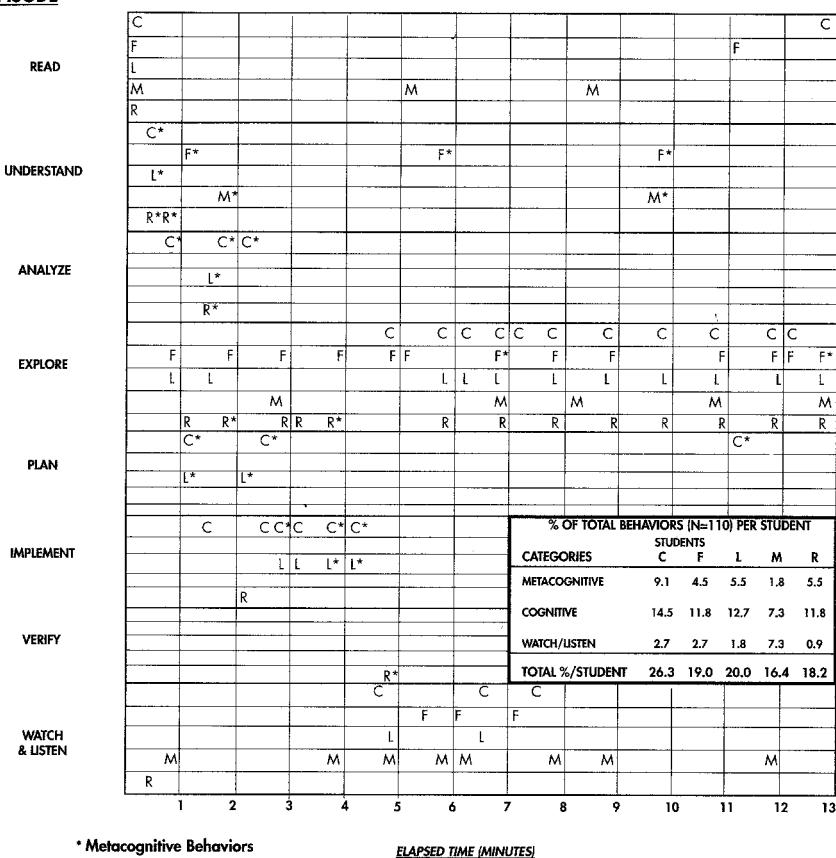
EPISODE

FIGURE 2 Diagram of behaviors in Group 1A.

within the group. The same is done for each member's cognitive behaviors and for watch and listen behaviors.

Metacognitive and Cognitive Behaviors

Table 3 shows the number and percentage of behaviors coded as metacognitive, cognitive, and watch and listen. Of 442 behaviors coded, 38.7% were metacognitive, 36.0% were cognitive, and 25.3% were in the watch and listen category, an undetermined cognitive level.

The metacognitive behaviors as a percentage of the total behaviors coded ranged from a low of 26.3% in Group 1A (the only group that did not solve the problem) to a high of 51.6% in Group 2A. The cognitive behaviors as a percentage of the total behaviors coded ranged from a low of 23.2% in Group 3B to a high

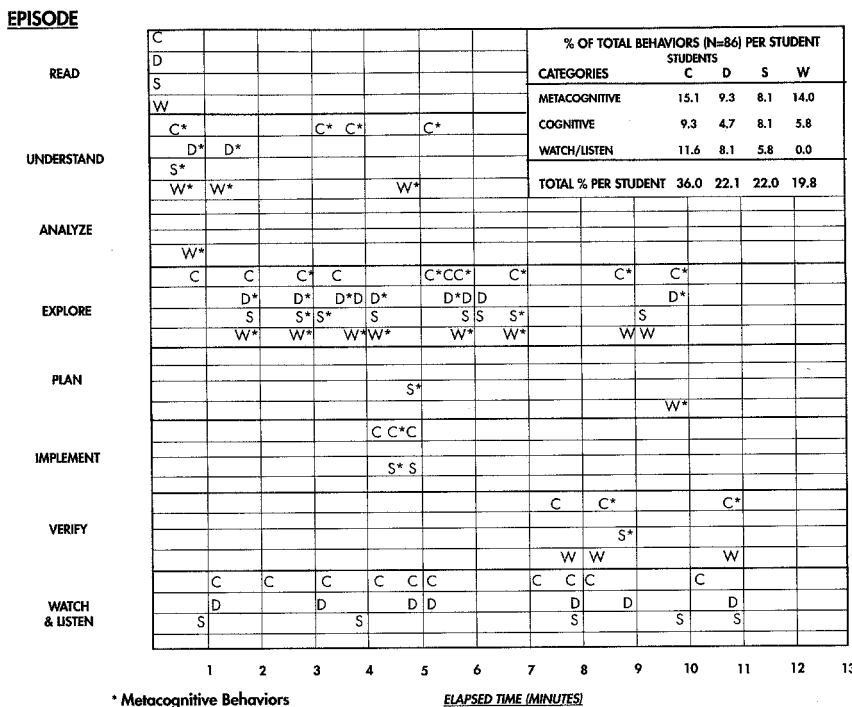


FIGURE 3 Diagram of behaviors in Group 3A.

of 58.2% in Group 1A. The ratio of metacognitive to cognitive behaviors ranged from a low of .45 in Group 1A to a high of 2.00 in Group 1B.

Problem-Solving Episodes and Cognitive Levels

Table 4 lists the percentage of cognitive and metacognitive behaviors coded by category for each group. Across all groups, there were 171 behaviors coded as metacognitive. Of these, 62 were in the category exploring (metacognitive), and 55 were in the category understanding. In other words, the greatest percentage of metacognitive behaviors was in exploring (36.3% of all metacognitive behaviors) and in understanding (32.2% of all metacognitive behaviors). In each of these categories, Group 1A had the lowest percentage of these behaviors—exploring (metacognitive), 3.6%, and understanding, 8.2%.

Across all groups, there were 159 behaviors coded as cognitive. Of these, 96 were in the category exploring (60.4% of all cognitive behaviors), and 38 were in the category reading (23.9% of all cognitive behaviors). In other words, the greatest percentage of cognitive behaviors was in exploring, followed by reading.

Of all the episodes coded, the exploring episode (metacognitive and cognitive together) was coded the greatest percentage of times in each group. The percent-

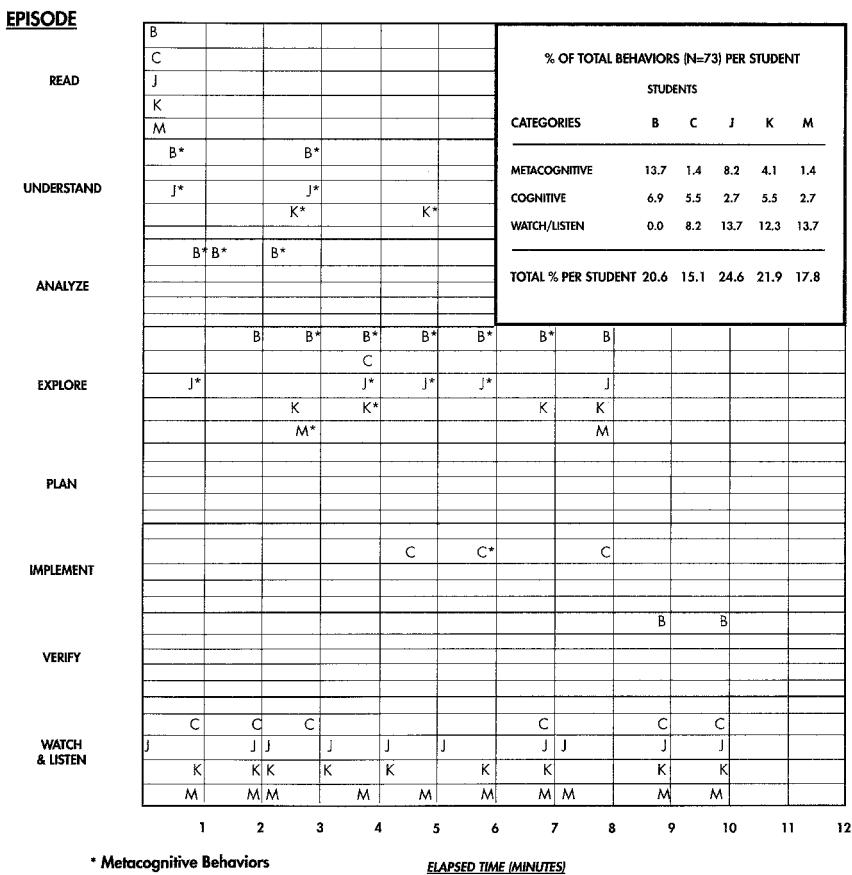


FIGURE 4 Diagram of behaviors in Group 3B.

age of total exploring episodes ranged from 25.3% in Group 1B to 48.0% in Group 1A. That is, in each group, at least one quarter of the episodes coded was in the exploring category.

In total, 112 coded behaviors were in the watch and listen category. Group 3B had the largest percentage of such behaviors (47.9%), and Group 1A had the smallest percentage (15.5%).

We elaborate on these findings in the Discussion section.

Stimulated-Recall Interviews of High-Ability Students

Although all students in the study were interviewed, this article focuses on the interviews of the highest ability student in each group, because they had the greatest potential to solve the mathematical problem. A summary of the narratives that

TABLE 3
Number (and Percentage) of Metacognitive, Cognitive, and Watch-and-Listen Behaviors Per Group

<i>Behavior Category</i>	<i>Group</i>						<i>Total</i>
	<i>1A</i>	<i>1B</i>	<i>2A</i>	<i>2B</i>	<i>3A</i>	<i>3B</i>	
Metacognitive	29 (26.3)	32 (47.7)	32 (51.6)	17 (38.7)	40 (46.5)	21 (28.8)	171 (38.7)
Cognitive	64 (58.2)	16 (23.9)	20 (32.2)	18 (40.9)	24 (28.0)	17 (23.2)	159 (36.0)
Watch and listen	17 (15.5)	19 (28.4)	10 (16.1)	9 (20.5)	22 (25.6)	35 (47.9)	112 (25.3)
Total	110 (100.0)	67 (100.0)	62 (100.0)	44 (100.0)	86 (100.0)	73 (100.0)	442 (100.0)

Note. Groups 1A, 2B, and 3B had five members; Groups 1B, 2A, and 3A had four members.

TABLE 4
Percent Distribution of Cognitive, Metacognitive, and Watch-and-Listen Behaviors
by Problem-Solving Group

<i>Behavior Category</i>	<i>Group</i>					
	<i>1A</i>	<i>1B</i>	<i>2A</i>	<i>2B</i>	<i>3A</i>	<i>3B</i>
Metacognitive						
Understand problem	8.2	17.9	21.0	11.4	11.6	8.2
Analyze	4.5	8.9	8.1	2.3	1.2	4.1
Explore	3.6	11.9	16.1	15.9	25.6	15.1
Plan	4.5	4.5	4.8	0.0	2.3	0.0
Implement	4.5	3.0	0.0	0.0	2.3	1.4
Verify	0.9	1.5	1.6	9.1	3.5	0.0
Cognitive						
Read	8.2	6.0	12.9	18.2	4.7	6.8
Explore	44.5	13.4	14.5	18.2	15.1	11.0
Implement	5.5	0.0	0.0	0.0	3.5	2.7
Verify	0.0	4.5	4.8	4.5	4.7	2.7
Watch and listen	15.5	28.4	16.1	20.5	25.6	47.9

focused on the students' attitudes about solving the problem in the small-group setting is presented next.

The highest ability members of Groups 2A, 2B, and 3A all revealed insecurities about their own abilities to solve the problem. They expressed their anxieties about the possibility of not being able to solve the problem on their own. They all expressed the desire to receive helpful input from their group members. In contrast, the highest ability members of Groups 1A, 1B, and 3B expressed their desires to work independently. One student revealed her belief that she would proceed more quickly by working alone. She also stated that she was "stubborn" and liked to do things her own way. Another claimed that he preferred to work alone, because that was the way he was "trained" and that is how one is expected to work on an exam. He also intimated that he lacked respect for the abilities of his group members.

The effect of these attitudes on the interactions that occurred within the groups is addressed in the Discussion section.

DISCUSSION

Framework and Cognitive Levels

The framework provides useful information with respect to when, where, and in what frequency group members use processes at the cognitive and metacognitive levels and how these levels of thought may affect the problem solution. It is possible that a certain balance of both cognitive and metacognitive processes

within a group is necessary for the problem-solving efforts to result in solution. Indeed, it is interesting that, in this study, the only group that did not solve the problem was the group with the lowest percentage of episodes at the metacognitive level and the highest percentage of episodes at the cognitive level. In fact, in this group, the ratio of metacognitive to cognitive behaviors was lower than any of the ratios of metacognitive to cognitive behaviors of the other five groups. It is also of interest to note that, during the exploratory phase of solving this problem, the unsuccessful group had, by far, the lowest percentage of metacognitive behaviors of all the groups.

Role of Metacognitive Behaviors

The current literature supports the importance of metacognitive behaviors such as active monitoring and subsequent regulation of cognitive processes during the act of problem solving (Baker & Brown, 1982; Flavell & Wellman, 1977; Garofalo & Lester, 1985; Schoenfeld, 1985b; Silver, 1987). When examining the specific instances of these types of metacognitive statements, one gets a better understanding of the ways in which they serve to enhance and propel the problem-solving process.

For example, the statement made by Student R in Group 1B (not reported in the earlier protocol), "We used every coin so far so we don't have to worry about it any more. So we have 41 cents, and we have 46 coins to use. We have to use more pennies," serves to help the group understand the status of the problem solution and the direction in which to go to continue the solution process. Other such statements made by different students were: "No, but you're getting confused 'cause this is the number of cents and this is the number of amount of coins"; and "Listen, if we have to use one of each, already we have 41 cents. We have 4 coins right? That means we need how many more coins? We need 46 more coins. So 46 coins and 41 cents. We have to break it down into nickels and pennies and everything else." Such statements often change the flow of conversation and appropriately redirect the efforts of the group members.

In a different way, the more "local" monitoring statements such as "No, that wouldn't work," "It's gotta be 50 coins," and "Use a lot of pennies" serve to control the group and to keep it from going off on wrong tangents by reminding the group members of the conditions of the problem that must be met and by suggesting the next small steps to take. As revealed by the transcriptions of the videotapes, these statements were made by all students who were caught up in the flow of the problem-solving process.

An example of what happens when there is an absence of consistent monitoring and regulating of the problem-solving process can be seen in Group 1A, which did not solve the problem. Student C declared the incorrect plan of using only nickels and pennies after they had 1 quarter and 1 dime. (The correct solution required 2 dimes.) If her plan had been monitored by another metacognitive state-

ment such as "That won't work" or "Maybe we should try using more dimes also," the group might have had a chance of getting back on track.

These results support the importance of metacognitive processes in mathematical problem solving in small-group settings. The framework developed in this study proved to be an effective tool for capturing the metacognitive behaviors characteristic of effective group work and of effective problem solving.

Role of Cognitive Behaviors

In this study, cognitive activity was evident in all groups. We have seen the important role of metacognitive statements; however, without the presence of students who were able to follow through or implement the metacognitive statements, the problem solving could not have been advanced or completed. For example, in the protocol of Group 3A, the students enacted a plan proposed by one of the group members. After completing the computation, they noticed that their solution was not satisfactory. Through the combined cognitive efforts of performing the calculations and metacognitive efforts of evaluating their solution, the students determined that they had to take a new approach, and thus the problem-solving process was advanced. The interrelationship between metacognitive and cognitive processes is complex, and an appropriate interplay between the two is necessary for successful problem solving to occur.

Role of Watching and Listening

The role of watching and listening is an important variable to consider when studying individuals solving problems in a small-group setting. Watching and listening are as much a part of communication as speaking is, and as Patton, Giffin, and Patton (1989) claimed, "Communication is the essence of the small-group experience" (p. 11).

Although in this study it was not possible to assign a cognitive level to such behavior, watching and listening play a major role in the group process. In fact, the degree of watching and listening behaviors of students may be the defining variable of whether students are engaged in a group interaction at all. For example, in Group 1A the students hardly listened to one another. Perhaps if they had, someone could have helped Student C change her inappropriate plan. Of all six groups, Group 1A had the lowest percentage of watch-and-listen behaviors. The inability of the students to share meanings prevented their group from functioning as a productive unit.

In contrast, most of the students in Group 3B were watching and listening while one person was doing the majority of the work. This is a different version of poor group functioning. Student B assumed a leadership role, and, because of his reported lack of respect for his fellow group members, he dominated the discussion with his own ideas. Research shows that such leadership styles discourage and inhibit the other group members from offering their input (Yukl, 1981). Of

all six groups, Group 3B had the highest percentage of watch-and-listen behaviors, none of which was contributed by Student B.

In contrast to the just-mentioned situations, the balance of watching and listening behaviors that occurred in Group 3A contributed to the fruitful interactions that took place. For example, after watching and listening for several minutes, Student D was able to contribute the helpful idea of using mostly pennies. One main advantage of working in a group is that students are able to benefit from group members' ideas. By listening to other people's ideas, one's own ideas are inspired. The extensive degree of interaction that occurred in Group 3A showed that each student was engaged in watching the activities and listening to the ideas of one another.

These examples support the group process theories that show the importance of communication skills for the effective functioning of the group. The balance of watching and listening behaviors during the group problem-solving process is an important issue to be given consideration.

Small-Group Setting

Observing Individuals in a Group Versus Observing a Group

The framework developed for this study was used to observe individual students as they worked in a small-group setting. The presence of group members affects the behaviors of the individual students in various ways and to different degrees. Moreover, in a classroom where the students are arranged in small groups, each group behaves in unique ways. The interactions of individuals working in small groups can be represented on a continuum that ranges from students who (although seated in a group) work independently and do not communicate with others to students who do interact with others in the solution of the problem. Between these two extremes is a multitude of possible scenarios. Figures 5a, 5b, 5c, and 5d depict several situations that can occur. In this study concerning only six groups, we saw a wide range of behavior patterns. For example, Group 1A was most like that depicted in Figures 5a and 5d where the students tended to work independently. Group 3A was a highly interactive group as depicted in Figure 5b, and Group 3B was the "one-man show" as depicted in Figure 5c.

In the literature, the term *group* has proved difficult to define. In fact, according to social psychologist Theodore Newcomb (1951), the term has never achieved a standard meaning. Definitions range from such loose requirements as a group being merely a collection of people (Homans, 1950) to more restrictive definitions that specify size and specific types of within-group communication (Patton et al., 1989). Generally, studies such as this one, which involve decision-making or problem-solving groups, adapt the more restrictive definitions. Patton et al. (1989) listed five conditions necessary for effective group work: (a) two or more people, (b) interdependence, (c) a common goal, (d) communication, and (e)

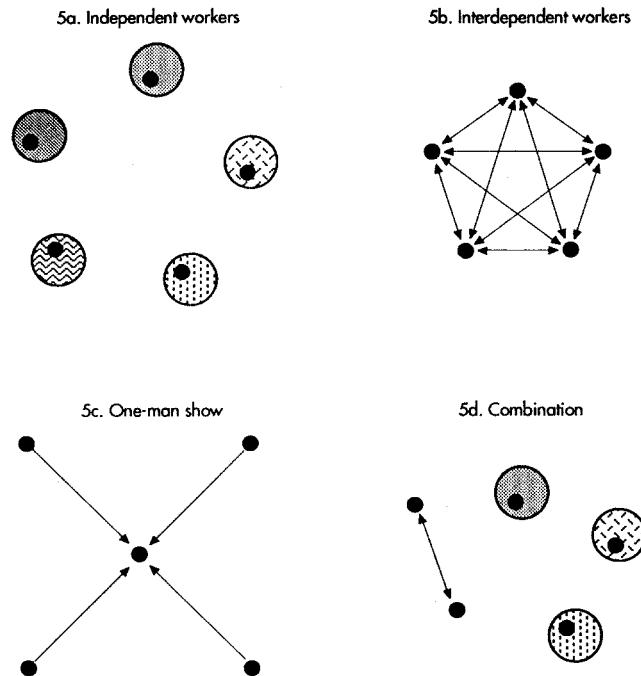


FIGURE 5 Patterns of group interactions.

norms. In the scenario depicted by Figure 5a in which each student works independently, there is little communication and thus ineffective group function. One might then question whether, in fact, this should really be considered a group (in the restrictive sense) or just five individuals seated in a group. At the other extreme, when the involvement of each individual becomes so integrated with the interactions of the other group members, the presence of individuals seems to disappear into the overall tapestry of the group. We have tried to examine the role of cognition and metacognition (as we have defined them) in problem solving in small-group settings by coding the behaviors of individual students. As the group behaviors tend to approach the scenario depicted in Figure 5b on the continuum, however, the behaviors of each of the group members become so interdependent that the group appears to take on its own "collaborative cognition," and the presence of individuals is almost lost.

Cognitive Processes Within a Small Group

The small-group format seems to encourage a spontaneous verbalization that allows the students to externalize their ideas for critical examination. The questioning, elaboration, explanation, and feedback to which these ideas are subjected

may be the mechanisms that account for problem solution. Research suggests that the small-grouping schemes that produce the most positive outcomes are structured to maximize these types of behaviors (Slavin, 1989–1990). That is, the most successful grouping strategies are carefully structured to ensure positive interdependence and individual accountability of group members. These structures serve as motivation for students to engage in the active participation within the group that creates an optimum setting for monitoring and regulating behaviors to occur. These are the metacognitive behaviors we have coded in the proposed framework. On this basis, it is reasonable to suspect that the most successful groups, in terms of both solving the problem and getting active involvement of all the group members, should be those with the highest percentages of metacognitive behaviors. In this study, the groups were not structured, although the behaviors of students in Group 3A resembled what would be expected in a group structured for positive interdependence and individual accountability. The results of this exploratory study seem to lend support for the idea that groups having all members actively involved have high incidences of metacognitive behaviors that may be the mechanisms by which problem solving is facilitated.

The diagrams in Figures 2, 3, and 4 represent the behaviors of the students in Groups 1A, 3A, and 3B that are highlighted here because of their contrasting characteristics. A comparison of these charts reveals an observable difference between Group 1A (Figure 2) and the other two groups (Figures 3 and 4). In Groups 3A and 3B, the exploration that occurred was monitored and regulated by group members (as indicated by the asterisks) throughout the duration of the problem-solving session. In Group 1A, there are only a few instances of monitored or regulated exploration. Interestingly, only Group 1A did not solve the problem, and, of all six groups, Group 1A had the lowest percentage of episodes of exploration at the metacognitive level (3.6%; see Table 4). In fact, Group 1A had the lowest total percentage of metacognitive behaviors (26.2%). A related, but not so obvious, difference between Group 1A and the other groups is the smaller percentage of students who were watching or listening to other students (15.5%). The inserted table in Figure 2 clearly shows that none of the students had a high percentage of watching and listening behaviors. In general, one sees this group functioning as individuals who, after the first 3 min, were all engaging in their own private unguided explorations. This is supported by the fact that the highest percentage of each student's individual behaviors was at the cognitive level.

The individualistic, unmonitored explorations of the members of Group 1A contrast with the apparent united effort of the students in Group 3A. (This is indicated in Figure 3 by the presence of all four group members' initials with asterisks in the exploration episodes.) The exploratory activities of this group were characterized by the idea sharing of all group members, accompanied by the subsequent monitoring and regulating of one another's ideas and approaches. The inserted table in Figure 3 shows that the greatest percentage of each student's

behavior was metacognitive. This contrasts with the behavior of the individual students in the other groups. From the observers' perspective, it appeared that this metacognitive behavior helped the students discover the solution to which each group member contributed.

Although the members of Group 3B also arrived at the solution, their main problem-solving activities appear to have been dominated by a few individuals (see Figure 4). Specifically, Student B was the driving force in this group. Note that this was the one student who had prior problem-solving experience. The asterisks indicate that Student B was sharing his ideas about the problem with the other students. However, aside from Student B, who did no watching and listening, the highest percentage of behaviors for each of the other students in the group was that of watching and listening. These data reflect the fact that one person dominated this group while the other group members mostly watched and listened.

Ability Levels

Why do groups take on such different behaviors? Why do the proportions of cognitive, metacognitive, and watch-and-listen behaviors differ so greatly among groups? What are the conditions that might bring a group to the highest level of group interaction and group productivity? Research efforts have provided abundant clues to the variables that are likely to impact positively or negatively on a group's performance. High on the list of influential variables are the communication skills, personalities, and intentions of the group members. In this small study, we can begin to investigate further a few ideas. For example, one may wonder how influential are the ability levels and the personalities and attitudes of the group members.

According to the ability data (Table 2), several groups had similar academic profiles (Groups 1A and 2B, Groups 3A and 3B, and Groups 1B and 2A). Despite these similarities, the groups functioned rather differently. Some variables that may have contributed to these differences were the personalities and attitudes of the highest ability member in each group.

For example, the students in Group 1A hardly worked together and were unsuccessful in solving the problem, whereas in Group 2B, aside from one student, the group members were very interactive and succeeded in solving the problem. In Group 1A, the highest ability member was admittedly unwilling to work with the other members of her group. She got fixed on one faulty plan and was not receptive to feedback from her peers. In contrast, in Group 2B, the highest ability member was admittedly insecure about her ability to solve the problem and expressed the desire to receive input from other group members.

A similar contrast existed between the behaviors of Groups 3A and 3B, despite their academic similarities. All the members in Group 3A were highly interactive and cooperative in solving the problem. In contrast, Group 3B was totally dominated by the highest ability member who solved the problem single-handedly

and discouraged input from his fellow group members. This student admittedly did not like, or see the purpose of, working with others. He had a competitive attitude and wanted to be the one in his group to solve the problem. Although he was able to solve the problem, he never helped any of his group members and was uninterested in their understanding of the problem. As might be expected, the highest ability member of Group 3A had a very different attitude about working in a group. She expressed a nervousness about the possibility of failing to be able to solve the problem. She said she was anxious to work with her group members in hopes that they would be able to help. Although, in the group, she was the one who made the most high-level metacognitive statements, she was totally influenced by and submerged in the problem solving in which the group was engaged.

In four of the six groups in this study, the highest ability student in each of the groups was primarily responsible for solving the problem. The two groups that did not fit this pattern were Group 1A, which did not solve the problem, and Group 3A, which was so interactive that it was impossible to assign credit to any one person in the group for having solved the problem.

It seems reasonable to conclude that the personalities and attitudes of the highest ability group members have a very powerful effect on the subsequent behaviors of each of the members of the group.

Framework and Heuristic Episodes

The framework was a useful tool for investigating the occurrence and frequency of heuristic episodes. It was evident that the episodes occurred intermittently in all six groups. In all groups, the students returned several times to different episodes. Most often, they returned to the words of the problem to gain a clearer understanding. They could often be heard reminding one another of the conditions that had to be met in the solution of the problem. In fact, all of the groups returned several times to the understanding episode. Most of the groups returned to reading several times. Figure 1 illustrates the ways in which the episodes can occur during a problem-solving session. One would imagine that each time the students returned to an episode they brought new insights with them. So, although they were at the same episode, they were there with a higher level of comprehension.

Exploring (cognitive and metacognitive together) was the behavior that was coded the greatest percentage of times. The exploratory phase, however, was most often accompanied by several other episodes as well. Exploration often led students to have an idea for a plan that, when deemed acceptable by the group members, led to an implementation. Often the implementation was fruitless, and the students returned to their exploration. In several cases, the exploration and analysis of the problem occurred intermittently. The exploration might have allowed the students to gain the familiarity with the problem that is a prerequisite

for analysis. In several groups, it appeared that the exploration sparked the analysis, which then sparked further exploration, and then more analysis. This sequence of behaviors looks very similar to the pattern of problem-solving behaviors of the expert mathematician that Schoenfeld (1985b) described in his study.

Framework and Type of Mathematical Problem

There is no question that the type of problem selected for the students to solve was an important variable in this study. Our banking problem was responsible for the high incidence of exploratory behaviors, because it lends itself to a trial-and-error approach. If the problem had been solvable through a more algorithmic approach, there probably would have been more evidence of systematic planning. In general, the type of problem used in this study affected the kinds of problem-solving approaches that might have been observed had a different problem been used. We acknowledge the important influence of context and content on problem-solving behavior, and we admit that the analysis of a single episode is a serious limitation of this study. The main purpose of this research, however, was to find out if the framework used for analyzing the behaviors of individuals as they worked on solving a mathematical problem in a small group showed evidence of being an effective tool. Once establishing that, we intend to apply it to multiple problems.

Study of Thought Processes

Researchers have begun to explore the small-group protocol (as opposed to a single-student or a "think-aloud" protocol) as a vehicle for studying mathematical problem solving, because observers are able to hear the thoughts of the students without interfering in the process (Hart, 1985; Noddings, 1982, 1985; Schoenfeld, 1985a; Silver, 1985). Unfortunately, there still exists a major difficulty in any research that aims to study thought processes. Even in a small group, thoughts are not always verbalized and, therefore, are not easily accessible to the observer. In this study, the only behaviors that could be categorized as metacognitive were those that were audible to the observers. If students were writing silently during episodes of exploration, implementation, and/or verification, their behaviors were categorized as cognitive. It is very possible that students were monitoring their work at these moments and that their metacognitive behaviors were overlooked. It is also possible that silent plans were overlooked as well.

Furthermore, when students work in small groups, they often watch and listen to one another. Because there is no verbalization at these times, it is impossible to assign a cognitive level to this activity. This problem adds an unknown variable to the results and has an effect on the percentages of reported cognitive and metacognitive behaviors. The stimulated-recall interviews were used to gain partial insight into these silent moments.

Compounding the methodological problem of coding was the theoretical complexity of the interplay of cognitive and metacognitive actions in problem solution. One source of the difficulty was identified by Brown (1978) as the difficulty of differentiating metacognitive from cognitive behaviors at both the theoretical and the empirical levels. And, as Sternberg (1985) pointed out, the difficulty is further compounded by the challenge of isolating the relative contributions of both cognitive and metacognitive actions to overall task performance.

CONCLUSION AND IMPLICATIONS

The purpose of this study was to examine the role of cognition and metacognition within the heuristic framework of mathematical problem solving in a small-group setting. A modification of Schoenfeld's framework was developed to delineate explicitly the type and level of processes used as individuals solved mathematical problems in small-group settings. Data analysis suggests the feasibility and usefulness of this framework for research of mathematical problem solving in small groups. With further study, the framework may be of pedagogical use to teachers.

The analysis of problem-solving behavior in the small-group protocols did provide some justification for the differentiation of metacognitive processes from cognitive processes. This is an important distinction with implications at both theoretical and practical levels. Different processes serve different important functions, and future research is needed to gain a better understanding of how interrelationships among processes affect the efficiency and effectiveness of problem solving. The framework also allowed an examination of the occurrence and frequency of heuristic episodes within small groups. The data suggest that, throughout the problem-solving session, students go back and forth using different heuristics intermittently. This behavior seems to play an important role in successful problem solving.

The stimulated-recall interviews provided insight about the attitudes students brought to their groups. Specifically, the attitudes of the high-ability group members manifested themselves in the subsequent behaviors of the group members. These results can provide important information to teachers and researchers who are interested in finding ways to maximize the effectiveness and efficiency of mathematical problem solving in small-group settings.

Most important, the framework shows promise as a powerful tool for the future study of individuals solving mathematical problems in a small-group setting. It can be used to study some of the key questions raised by this study:

1. What is the balance of cognitive, metacognitive, and watch-and-listen behaviors that is most favorable for productive group problem solving?
2. What is the balance of individual group members' contributions that is most favorable for productive group problem solving?

3. When is group problem solving really group problem solving? How should group problem solving be defined?
4. What role does the sequence of heuristic episodes play in the solution of a mathematical problem?
5. What effect do different types of problems have on the heuristic processes used in group problem solving?
6. What is the role of dialogue in small-group settings? More specifically, is there evidence of social scaffolding that occurs naturally in well-structured groups?

Research on questions such as these can begin to be addressed through the application of the framework developed here.

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APPENDIX

Cognitive-Metacognitive Framework for Protocol Analysis of Problem Solving in Mathematics

The following framework outlines the interactive relationship between metacognitive and cognitive processes in mathematical problem solving. The episodic categories are described theoretically and empirically. The level or levels of cognition associated with each category are indicated as well. Note that during the course of problem solving these episodes need not occur in the order listed, may occur several times, and may indeed be bypassed completely.

Episode 1: Reading the problem (cognitive)

Description: The student reads the problem.

Indicators: The student is observed as reading the problem or listening to someone else read the problem. The student may be reading the problem silently or aloud to the group.

Episode 2: Understanding the problem (metacognitive)

Description: The student considers domain-specific knowledge that is relevant to the problem. Domain-specific knowledge includes recognition of the linguistic, semantic, and schematic attributes of the problem in his or her own words and represents the problem in a different form.

Indicators: The student may be exhibiting any of the following behaviors: (a) restating the problem in his or her own words; (b) asking for clarification of the meaning of the problem; (c) representing the problem by writing the key facts or by making a diagram or list; (d) reminding himself or herself or others of the requirements of the problem, for example, "Remember, we must use the exact number that is asked for in the problem"; (e) stating or asking himself or herself whether he or she has done a similar problem in the past; and (f) discussing the presence or absence of important pieces of information.

Episode 3: Analyzing the problem (metacognitive)

Description: The student decomposes the problem into its basic elements and examines the implicit or explicit relations between the givens and goals of the problem.

Indicators: The student is engaging in an attempt to simplify or reformulate the problem. An attempt is made to select an appropriate perspective of the problem and to reformulate it in those terms. Examples of statements reflecting that such analysis is occurring are: "After you use all the given information, it becomes an easy problem of addition," and "Because the total is a multiple of five, I think the answer must be divisible by five."

Episode 4: Planning (metacognitive)

Description: The student selects steps for solving the problem and a strategy for combining them that might potentially lead to problem solution if implemented. The student may also select a representation for the information in the problem. In addition, the student may assess the status of the problem solution and make decisions for change if necessary.

Indicators: The student describes an approach that he or she intends to use to solve the problem. This may be in the form of steps to be taken or strategies to be used. Examples of statements that reflect planning include the following: "Let's use the given information first and see what the problem looks like after that"; "Let's work backwards by estimating an answer and see how it must be adjusted to fit the problem"; "Let's draw a chart and fill in the numbers"; "Let's think of a different way to go about this"; and "Let's check back to see where we went wrong."

Episode 5a: Exploring (cognitive)

Description: The student executes a trial-and-error strategy in an attempt to reduce the discrepancy between the givens and the goals.

Indicators: The student engages in a variety of calculations without any apparent structure to the work. There is no visible sequence to the operations performed by the student.

Episode 5b: Exploring (metacognitive)

Description: The student monitors the progress of his or her or others' attempted actions thus far and decides whether to terminate or continue working through the operations. This differs from analysis in that it is less well

structured, and it is further removed from the original problem. If one comes across new information during exploration, he or she may return to analysis in the hope of using that information to better understand the problem.

Indicators: (a) The student draws away from the problem to ask himself or herself or someone else what has been done during the exploration. Examples of such statements are: "What are you doing?" and "What am I doing?" (b) The student gives suggestions to other students about what to try next in the exploration. An example of such a comment is: "It's getting too big; try it with one less." (c) The student evaluates the status of the exploration. Examples of such statements are: "This isn't getting us anywhere," and "I think that's the answer!"

Episode 6a: Implementing (cognitive)

Description: The student executes a strategy that grows out of his or her understanding, analysis, and/or planning decisions and judgments. Unlike exploration, the student's actions are characterized by a quality of systematicity and deliberateness in transforming the givens into the goals of the problem.

Indicators: The student appears to be engaging in a coherent and well-structured series of calculations. There is evidence of an orderly procedure.

Episode 6b: Implementing (metacognitive)

Description: The student engages in the same kind of metacognitive process as in the exploring (metacognitive) phase of problem solving, monitoring the progress of his or her attempted actions. Unlike the exploratory phase, however, the metacognitive decisions build on, check, or revise those previously considered decisions. Furthermore, the student may consider a reallocation of his or her problem-solving resources, given the time constraint within which the problem must be solved.

Indicators: During the implementation phase, the student draws away from the work to see what has been done or where it is leading. The following examples of statements reflect this: "Okay, I used all the given conditions, and now I will start adding what is left"; "Wait. You forgot to use the second point"; and "This is taking too long. Try skipping the odd numbers."

Episode 7a: Verifying (cognitive)

Description: The student evaluates the outcome of the work by checking computational operations.

Indicators: The student redoing the computational operations he or she did before to check that it was done correctly.

Episode 7b: Verifying (metacognitive)

Description: The student evaluates the solution of the problem by judging whether the outcome reflected adequate problem understanding, analysis, planning, and/or implementation. Should the student discover a discrepancy in this comparison search, he or she engages in new decision making for correcting the faulty metacognitive and/or cognitive processing that led

to the incorrect solution. The ability to adjust one's thinking on the basis of evaluative information is another indication of self-regulatory competence. Should the evaluation of problem solution indicate an adequacy of or congruence with metacognitive and cognitive processing, the mental reiteration ends.

Indicators: After the student has decided that the solution or part of the solution has been obtained, he or she may review the work in several ways: (a) The student checks the solution process to see whether it makes sense. For example, "When we simplified the problem, did we use all of the given information?" (b) The student checks to see if the solution satisfies the conditions of the problem. For example, "Does our answer satisfy both of the properties that were asked for?" (c) The student explains to a groupmate how the solution was obtained. For example, "I knew it had to be a big number, so I started with the largest numbers first."

Episode 8: Watching and listening (uncategorized)

Description: This category only pertains to students who are working with other people. The student is attending to the ideas and work of others.

Indicators: The student appears to be listening to a group member who is talking or watching a group member who is writing.

DEVELOPMENT OF LEARNING STRATEGY RECOMMENDATION SYSTEM TO TRAIN METACOGNITION AND SELF-REGULATED LEARNING IN ALGORITHM AND DATA STRUCTURE COURSE

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ABSTRACT

Metacognitive training system (MTS) which is developed for Algorithm and Data Structure course facilitates students to choose, use, and evaluate different learning strategies. Therefore, students are encouraged to be self-regulated. However, the system is also expected to know the best learning strategies of students to generate recommendation that will help students to better understand their self. The recommendation is generated by using various parameters such as post-test scores, learning strategy evaluation values, learning strategy access time, number of clicks and number of summary words to determine the best level of metacognition and learning strategies for students. The learning strategy recommendation system developed using Simple Additive Fuzzy Weighting Algorithm. This method adds the weight of each criterion in each learning strategy. The system's functionality is tested using Black Box method as well as validated by experts. A user acceptance test (UAT) is also carried out to prove that the system is accepted by users and requirements have been met. The UAT resulted in an average of 82.5% which is considered as very good.

KEYWORDS

Metacognitive training system, self-regulated learning, recommendation system, e-learning.

1. INTRODUCTION

A metacognitive training system (MTS) is a system to train students' metacognitive skills and self-regulated learning (SRL). Previously, an MTS which is aimed to support students in learning algorithm and data structure was developed. The developed MTS provides some different learning strategies, namely drawing, summarizing, and controlling video to be used by students according to their individual preference (Nurlayli, Adji, Permanasari, & Hidayah, 2017). The first learning strategy, i.e. drawing, is a strategy that gives students a learning material which is complemented with a tool for drawing a mind map about the learning topic. The second strategy is summarizing in which students will be provided with tool for summarizing the learning material into a short paragraphs. Lastly, controlling video learning strategy, it is a strategy that gives students a video complemented with controlling tools.

Given the three learning strategies, students are free to use one of them. After that, they must evaluate the effectiveness of the strategy and revise when needed. Therefore, students are encouraged to identify the best strategy for each of them. However, it is found in the testing phase that students need a learning strategy recommendation system to further support their learning (Nurlayli, Adji, Permanasari, & Hidayah, 2017). It is expected that the system can provide insight of the most appropriate strategy for each student in practicing metacognition and self-regulated skills in the learning process.

Therefore, the aim of this current study is to design, develop, and evaluate a system which generates learning strategy recommendation for each unique student. To generate the recommendation two types of parameters are used, including offline and online parameters. Offline parameters in this case are collected by the use of self-report questionnaire. The questionnaire is used as a self-report instrument to evaluate previous learning strategies. Online parameters are composed from two components. First component of online parameters are the log of user interactions when using a learning strategy, such as the number of clicks, the number of words and the study duration. The second component is the result of learning outcome assessment.

2. LITERATURE REVIEW

Metacognition is an important success factor for student learning. When someone has reached a good level of certain metacognition, a person can do self-regulated learning (SRL), which is how a student can be a self-regulator for his own learning. SRL also means monitoring of behavior in the learning process as a result of the metacognition process of goals, planning, and self-appreciation for the achievements that have been achieved (Zimmerman & Pons, 1986) (Poitras & Lajoie, 2013).

One of the support systems in increasing the level of metacognition and SRL is the metacognitive training system (MTS). With MTS, the process of improving metacognition can be done during the learning process. Presently, metacognitive training systems are developed in several learning topics, such as biology (Azevedo, Johnson, Chauncey, & Burkett, 2010) and mathematics (Cueli, González-castro, Krawec, Núñez, & González-pienda, 2016). However, for engineering disciplines, the implementation of metacognitive training system is hardly found. Algorithm learning as a fundamental course in information engineering school is emphasized to develop the ability to analyze computing problem and to design a possible computing solution. Thus, metacognitive training to be implemented must support the development of problem-solving skill (Combefis, Barry, Crappe, & David, 2017). Furthermore, the presence of recommendation from the system will guide and ensure the effectiveness of the training system.

Recommendation systems are developed based on users profile or model (Santos & Boticario, 2015). Where, student model is the simplified representation of the student which defines the character of the student. There are several machine learning techniques for student modeling, such as fuzzy inference system (Hidayah, Permanasari, & Ratwastuti, 2013). Fuzzy inference system has been demonstrated to improve adaptivity of e-learning systems. Therefore, the technique is going to be explored in this study.

3. METHOD

The simple additive weighting (SAW) method is a method of adding the weight of each parameter used in a study. The basic concept of this method is to add up the weighting of the performance rating on the alternatives available on all attributes. The SAW method requires a normalization of the decision matrix and the weights. This method has 2 attribute criteria, which are profit criteria and cost criteria. The benefit criteria have a greater value if the level of compatibility is higher. The cost criterion will have a smaller value if the compatibility level is higher. The SAW method is often used in solving multiple attribute decision making

problems as in this study (Fahrurrozi & Gautama, 2013). The equation for computing SAW is in (1), where V_i is the value of user's preference on each alternative.

$$V_i = \sum_{j=1}^n w_j r_{ij} \quad (1)$$

Learning strategy evaluation questions are questions compiled which is aimed to get feedback from users after using a learning strategy. This evaluation question is displayed when students complete a learning step by using his/her learning strategy. These evaluation questions are based on (Talby, Nakar, Shmueli, Margolin, & Keren, 2005; Permana, 2017) regarding collaborative applications in e-Learning strategies. These questions are listed in Table 1.

Table 1. Questions for self-evaluation on used learning strategy

No	Question
1	Are you confident in using this learning strategy?
2	Does the learning strategy provide information that can be easily understood?
3	Can you collaborate with the learning strategy?
4	Are you innovated to learn more when using these learning strategies?
5	Have your learning objectives been achieved with this learning strategy?
6	Did you get feedback from the learning strategy?
7	Can you feel focused when using the learning strategy?
8	Are you encouraged to use the learning strategy again?
9	Can you conclude the learning material learned from the learning strategy?
- 10	Do you understand texts, pictures or videos based on these learning strategies?

Each question has been considered by the developer according to the needs of the recommendation system. The first question was chosen to find out the ease of receiving information from learning strategies to students. The second question is made to find out the material and learning strategies that are of interest to students. The third question was chosen to find out the resilience and level of focus of students in using learning strategies. The fourth question is the most important chosen to find out the students' interest in using learning strategies. The fifth question was chosen to find out the continuation and development of learning strategies going forward. The sixth question is to determine the ability of students to take the essence of the learning strategy undertaken. These five questions have been considered against the factors associated with e-Learning system feedback (Talby, Nakar, Shmueli, Margolin, & Keren, 2005).

User acceptance test (UAT) is a formal test carried out to determine system acceptance from the user's point of view. The accepted system meets the acceptance criteria based on the user Hambling & Van Goethem, 2013). UAT has three main contributions as follows:

1. Complete the system requirements with direct verification with the user.
2. Reveal other problems that have not been found in the system for continued system development.
3. Gives the completed status on the system that the user has accepted.

In developing the system, a UAT survey questionnaire will be used aimed at the user. The questionnaire that is based on Hambling & Van Goethem, 2013) can be seen in Table 2.

Table 2. Questions for user acceptance test (Hambling & Van Goethem, 2013)

Question	A	B	C	D	E
Is this learning web look interesting?					
Are the learning web menus easy to understand?					
Is this web learning media material easy to understand?					
Are there examples that help understand the material?					
Is the evaluation on this learning web appropriate?					
Does evaluation help measure material understanding?					
Can this web learning media be used as a learning aid media?					
Is this web learning media good enough?					

Each question has 5 answer options from A to E. Information on the answer options can be seen in Table 3. The answer options have different weights in accordance with the provisions of the UAT weighting table. Answer A has a weight times 5, B has a weight times 4, C has a weight times 3, D has a weight times 2, and E has a weight times 1.

Table 3. Definition on each option of the answer in UAT

Option	Definition
A	Very: easy/good/appropriate/clear
B	Easy/good/appropriate/clear
C	Neutral
D	Fair: easy/good/appropriate/clear
E	Very: difficult/bad/inappropriate/unclear

This test requires at least 15 respondents to obtain the ideal acceptance results (Halimah, 2010). In the test, there will be a survey of at least 15 students who have taken the Algorithm and Data Structure courses from various forces.

4. RESULT AND DISCUSSION

The use case diagram of the recommendation system can be seen in Figure 1. It presents a picture model of various functions and interactions that can be operated by actors in the developed metacognitive training system. Meanwhile, some activities in the system can be executed in order or not. In making it easy to understand the sequence of activities from beginning to end, all activities in the system are described in the Activity Diagram in Figure 2.

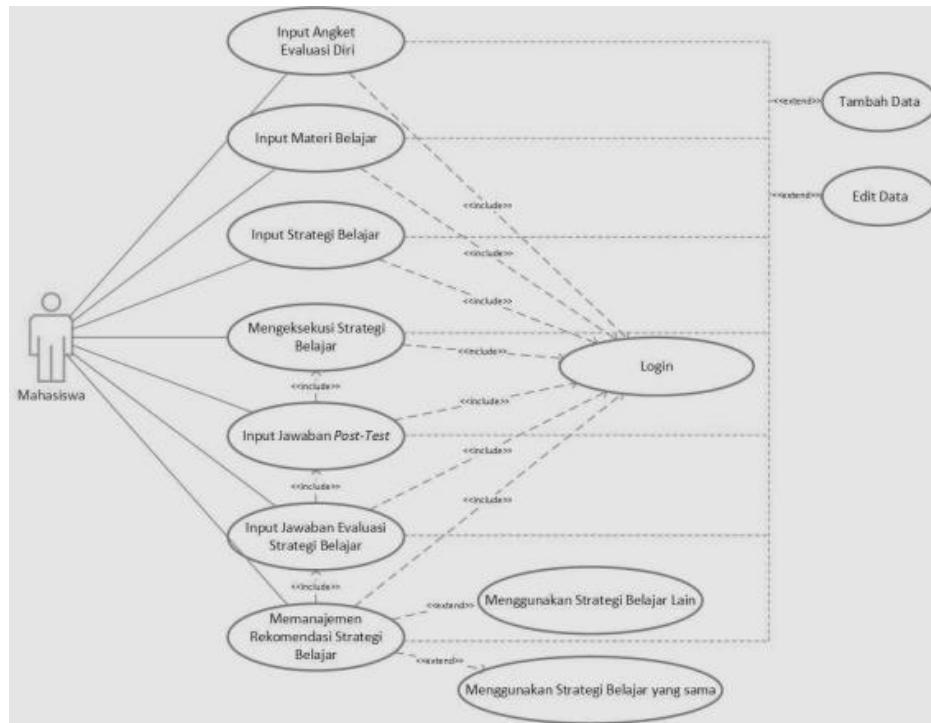


Figure 1. Use case diagram

As shown in Figure 2, login activity is carried out to open the functions and features in it. When a student successfully logs in, the system will display the Self Evaluation Questionnaire page and the student will fill in the Self Evaluation Questionnaire and the system will store it in the database. After that, the system will direct students to a page that contains learning material offered and students will input the desired learning material. If you have inputted learning material, the system will direct students to a page that lists the learning strategies offered. The list of learning strategies that are displayed will be chosen by students and the system will store the results of the input into the database.

The learning strategy recommendation system was developed using 2 decision making methods, namely by using a decision table and the Simple Additive Fuzzy Weighting (SAFW) algorithm. The Decision Table will establish a recommendation system based on student statement and grade in each criterion used in each learning strategy and the SAFW Algorithm maps the "gray area" of the total criteria value that is still unreached by the decision table such as students who get the middle criterion value on each criteria. The Decision Table has applied Fuzzy Logic to certain criteria so that there are not only pass and not pass. SAFW algorithm can be said as an amplifier of the decision table.

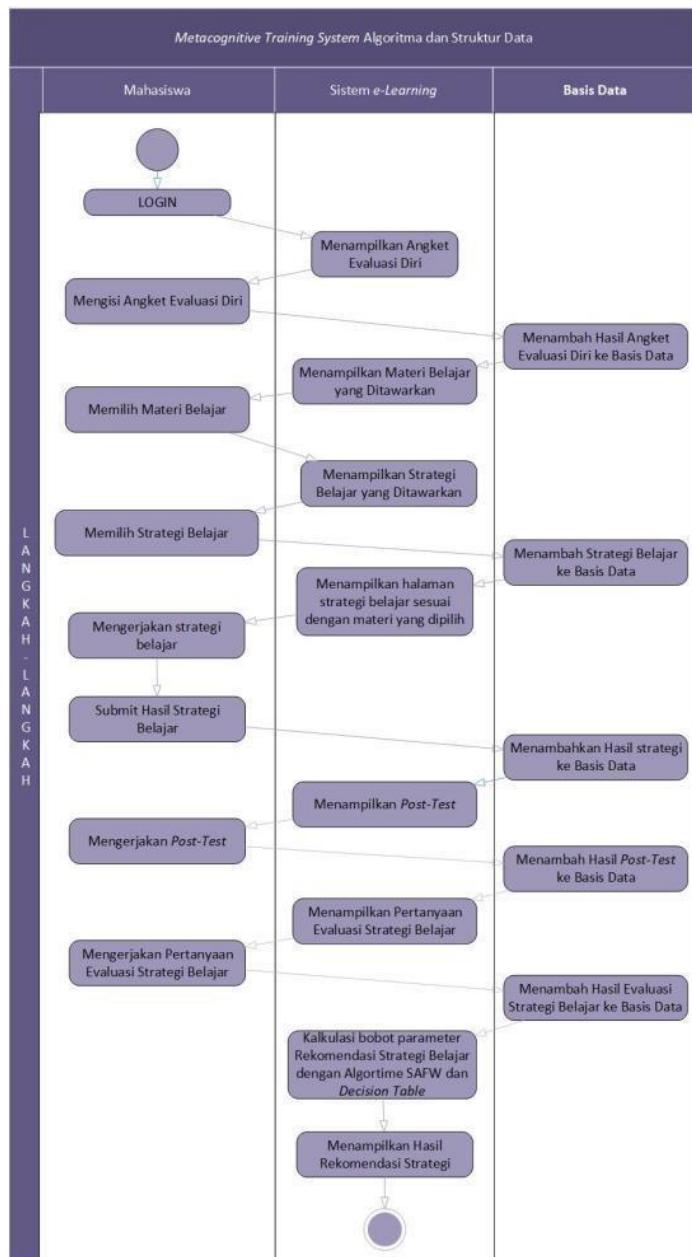


Figure 2. Activity diagram

The most difficult part in the study is in defining the value of the criteria, because there is no previous research on the learning strategy recommendation system using user behavior criteria. For example, we need to use number of clicks as an indicator for match/no-match with a learning strategy, e.g. controlling video. To answer this question, a survey is conducted which resulting in some values as listed in Table 4. For example, a student make 17 of clicks when using a controlling video learning strategy, thus, he can be categorized as medium match to the strategy.

Table 4. Relation of number of clicks and categorization of match

Learning strategy	Low	Medium	High
Video	0-4 and >36	5-9 and 16-35	10-15
Draw	0-25 and >70	26-35 and 46-70	34-45

Data log of students' interaction with the system are recorded the results of each of these criteria and calculate the Simple Additive Fuzzy Weighting algorithm.

The calculation of UAT results of question number 1 is 70.5%, question 2 is 78.8%, question 3 is 82.4%, question 4 is 82.4%, question 5 is 89.4%, question 6 is

91.7 %, question 7 is 84.7% and Question 8 is worth 80%. The result indicates that the recommendation system has an attractive appearance, the menus on the web media are quite easy to understand, the content or material is easily understood and understood with examples of material, evaluations are already available, this web learning media can also be used as a media learning aids and learning media web is good.

5. CONCLUSION

Based on the evaluation result, the learning strategy recommendation system can adjust student preferences. Several criteria such as post-test, learning strategy evaluation questions and user behavior such as the number of clicks, the number of words and the amount of time can be used to determine the learning strategy recommendations.

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Hybrid recommender systems: A systematic literature review

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Abstract. Recommender systems are software tools used to generate and provide suggestions for items and other entities to the users by exploiting various strategies. Hybrid recommender systems combine two or more recommendation strategies in different ways to benefit from their complementary advantages. This systematic literature review presents the state of the art in hybrid recommender systems of the last decade. It is the first quantitative review work completely focused in hybrid recommenders. We address the most relevant problems considered and present the associated data mining and recommendation techniques used to overcome them. We also explore the hybridization classes each hybrid recommender belongs to, the application domains, the evaluation process and proposed future research directions. Based on our findings, most of the studies combine collaborative filtering with another technique often in a weighted way. Also cold-start and data sparsity are the two traditional and top problems being addressed in 23 and 22 studies each, while movies and movie datasets are still widely used by most of the authors. As most of the studies are evaluated by comparisons with similar methods using accuracy metrics, providing more credible and user oriented evaluations remains a typical challenge. Besides this, newer challenges were also identified such as responding to the variation of user context, evolving user tastes or providing cross-domain recommendations. Being a hot topic, hybrid recommenders represent a good basis with which to respond accordingly by exploring newer opportunities such as contextualizing recommendations, involving parallel hybrid algorithms, processing larger datasets, etc.

Keywords: Hybrid recommendations, recommender systems, systematic review, recommendation strategies

1. Introduction

Historically people have relied on their peers or on experts' suggestions for decision support and recommendations about commodities, news, entertainment, etc. The exponential growth of the digital information in the last 25 years, especially in the web, has created the problem of information overload. Information overload is defined as “stress induced by reception of more information than is necessary to make a decision and by attempts to deal with it with outdated time management practices”¹. This problem limits our capacity to review the specifications and choose between numerous alternatives of items in the online market. On the other hand, information science and technology reacted accordingly by developing information filtering tools to alleviate the problem. Recommender Systems (RSs) are one such tools that emerged in the mid 90s. They are commonly defined as software tools and techniques used to provide suggestions for items and other recommendable entities to users [1]. In the early days

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¹<http://www.businessdictionary.com/definition/information-overload.html>.

(beginning of 90s) RSs were the study subject of other closely related research disciplines such as Human Computer Interaction (HCI) or Information Retrieval (IR) [2]. Today, RSs are found everywhere helping users in searching for various types of items and services. They also serve as sales assistants for businesses increasing their profits.

Technically all RSs employ one or more recommendation strategies such as Content-Based Filtering (CBF), Collaborative Filtering (CF), Demographic Filtering (DF), Knowledge-Based Filtering (KBF), etc. described below:

- **Collaborative filtering:** The basic assumption of CF is that people who had similar tastes in the past will also have similar tastes in the future. One of its earliest definitions is “collaboration between people to help one another perform filtering by recording their reactions to documents they read” [3]. This approach uses ratings or other forms of user generated feedback to spot taste commonalities between groups of users and then generates recommendations based on inter-user similarities [2]. CF recommenders suffer from problems like cold-start (new user or new item), “gray sheep” (users that do not fit in any taste cluster), etc.
- **Content-based filtering:** CBF is based on the assumption that people who liked items with certain attributes in the past, will like the same kind of items in the future as well. It makes use of item features to compare the item with user profiles and provide recommendations. Recommendation quality is limited by the selected features of the recommended items. Same as CF, CBF suffer from the cold-start problem.
- **Demographic filtering:** DF uses demographic data such as *age, gender, education*, etc. for identifying categories of users. It does not suffer from the new user problem as it doesn't use ratings to provide recommendations. However, it is difficult today to collect enough demographic information that is needed because of online privacy concerns, limiting the utilization of DF. It is still combined with other recommenders as a reinforcing technique for better quality.
- **Knowledge-based filtering:** KBF uses knowledge about users and items to reason about what items meet the users' requirements, and generate recommendations accordingly [4]. A special type of KBFs are constraint-based RSs which are capable to recommend complex items that are rarely bought (i.e. cars or houses) and manifest important constraints for the user (price) [5]. It is not possible to successfully use CF or CBF in this domain of items as few user-system interaction data are available (people rarely buy houses).

One of the earliest recommender systems was Tapestry, a manual CF mail system [3]. The first computerized RS prototypes also applied a collaborative filtering approach and emerged in mid 90s [6,7]. GroupLens was a CF recommendation engine for finding news articles. In [7] the authors present a detailed analysis and evaluation of the Bellcore video recommender algorithm and its implementation embedded in the Mosaic browser interface. Ringo used taste similarities to provide personalized music recommendations. Other prototypes like NewsWeeder and InfoFinder recommended news and documents using CBF, based on item attributes [8,9]. In late 90s important commercial RS prototypes also came out with Amazon.com recommender being the most popular. Many researchers started to combine the recommendation strategies in different ways building hybrid RSs which we consider in this review. Hybrid RSs put together two or more of the other strategies with the goal of reinforcing their advantages and reducing their disadvantages or limitations. One of the first was Fab, a meta-level recommender (see Section 3.4.6) which was used to suggest websites [10]. It incorporated a combination of CF to find users having similar website preferences, with CBF to find websites with similar content. Other works such as [11] followed shortly and hybrid RSs became a well established recommendation approach.

The continuously growing industrial interest in the recent and promising domains of mobile and social web has been followed by a similar increase of academic interest in RSs. ACM RecSys annual conference² is now the most significant event for presenting and discussing RS research. The work of Burke in [12] is one of the first qualitative surveys addressing hybrid RSs. The author analyzes advantages and disadvantages of the different recommendation strategies and provides a comprehensive taxonomy for classifying the ways they combine with each other to form hybrid RSs. He also presents several hybrid RS prototypes falling into the 7 hybridization classes of the taxonomy. Another early exploratory work is [13] where several experiments combining personalized agents with opinions of community members in a CF framework are conducted. They conclude that this combination produces high-quality recommendations and that the best results of CF are achieved using large data of user communities. Other review works are more generic and address RSs in general, not focusing in any RS type. They reflect the increasing interest in the field in quantitative terms. In [14] the authors perform a review work of 249 journal and conference RS publications from 1995 to 2013. The peak publication period of the works they consider is between 2007 and 2013 (last one-third of the analyzed period). They emphasize the fact that the current hybrid RSs are incorporating location information into existing recommendation algorithms. They also highlight the proper combination of existing methods using different forms of data, and evaluating other characteristics (e.g., diversity and novelty) besides accuracy as future trends. In [15] the authors review 210 recommender system articles published in 46 journals from 2001 to 2010. They similarly report a rapid increase of publications between 2007 and 2010 and predict an increase interest in mixing existing recommendation methods or using social network analysis to provide recommendations.

In this review paper we summarize the state of the art of hybrid RSs in the last 10 years. We follow a systematic methodology to analyze and interpret the available facts related to the 7 research questions we defined. This methodology defined at [16,17] provides an unbiased and reproducible way for undertaking a review work. Unlike the other review works not focused in any RS type [14,15], this systematic literature review is the first quantitative work that is entirely focused in recent hybrid RS publications. For this reason it was not possible for us to have a direct basis with which to compare our results. Nevertheless we provide some comparisons of results for certain aspects in which hybrid RSs do not differ from other types of RSs. To have a general idea about what percentage of total RS publications address hybrid RSs we examined [18], a survey work about RSs in general. Here the authors review the work of 330 papers published in computer science and information systems conferences proceedings and journals from 2006 to 2011. Their results show that hybrid recommendation paradigm is the study object of about 14.5% of their reviewed literature.

We considered the most relevant problems hybrid RSs attempt to solve, the data mining and machine learning methods involved, RS technique combinations the studies utilize and the hybridization classes the proposed systems fall into. We also observed the domains in which the contributions were applied and the evaluation strategies, characteristics and metrics that were used. Based on the suggestions of the authors and the identified challenges we also present some future work directions which seem promising and in concordance with the RS trends. Many primary studies were retrieved from digital libraries and the most relevant papers were selected for more detailed processing (we use the terms paper and study interchangeably to refer to the same object/concept). We hope this work will help anyone working in the field of (hybrid) RSs, especially by providing insights about future trends or opportunities. The remainder of the paper is structured as follows. Section 2 briefly summarizes the methodology we followed, the objectives and research questions defined, the selection of papers and the quality assessment process.

²<https://recsys.acm.org/>.

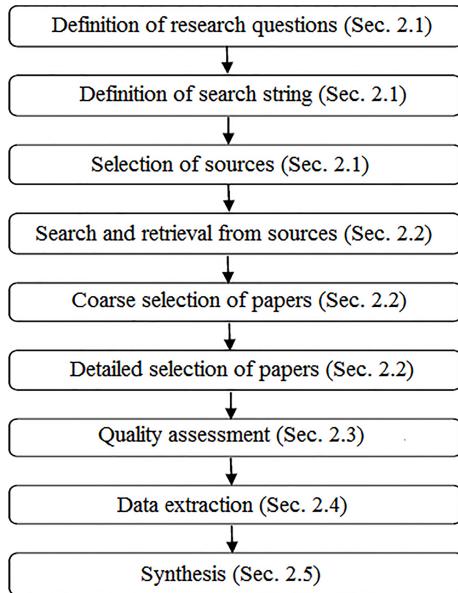


Fig. 1. Systematic literature review protocol.

Section 3 introduces the results of the review organized in accordance with each research question. Section 4 discusses and summarizes each result whereas Section 5 concludes. Finally we list the selected papers in Appendix.

2. Methodology

The review work of this paper follows the guidelines that were defined by Kitchenham and Charters [17] for systematic literature reviews in Software Engineering. The purpose of a systematic literature review is to present a verifiable and unbiased treatment of a research topic utilizing a rigorous and reproducible methodology. The guidelines that were followed are high level and do not consider the influence of research questions type on the review procedures. In Fig. 1 we present the protocol of the review. It represents a clear set of steps which assist the management of the review process. The protocol was defined by the first author and verified by the second author. In the following sections we describe each step we summarized in Fig. 1.

2.1. Research questions, search string and digital sources

The primary goal of this systematic literature review is to understand what challenges hybrid RSs could successfully address, how they are developed and evaluated and in what ways or aspects they could be experimented with. To this end, we defined the following research questions:

RQ1 What are the most relevant studies addressing hybrid recommender systems?

RQ2 What problems and challenges are faced by the researchers in this field?

RQ3a Which data mining and machine learning techniques are used in hybrid RSs?

RQ3b What recommendation techniques are combined and which problems they solve?

RQ4 What hybridization classes are used, based on the taxonomy of Burke?

Table 1
Selected sources to search for primary studies

Source	URL
SpringerLink	http://link.springer.com
Science direct	http://www.sciencedirect.com
IEEEExplore	http://ieeexplore.ieee.org
ACM digital library	http://dl.acm.org
Scopus	http://www.scopus.com

Table 2
Keywords and synonyms

Keyword	Synonyms
Hybrid	Hybridization, Mixed
Recommender	Recommendation
System	Software, Technique, Technology, Approach, Engine

Table 3
Inclusion and exclusion criteria

Inclusion criteria
Papers presenting hybrid recommender systems, algorithms, approaches, etc.
Papers that even though do not specifically present hybrid RSs, provide recommendations combining different data mining techniques.
Papers from conferences and journals
Papers published from 2005 to 2015
Papers written in English language only
Exclusion criteria
Papers not addressing recommender systems at all
Papers addressing RSs but not implying any hybridization or combination of different approaches or data mining techniques.
Papers that report only abstracts or slides of presentation, lacking detailed information
Grey literature

RQ5 In what domains are hybrid recommenders applied?

RQ6a What methodologies are used for the evaluation and what metrics they utilize?

RQ6b Which RS characteristics are evaluated and what metrics they use?

RQ6c What datasets are used for training and testing hybrid RSs?

RQ7 Which directions are most promising for future research?

Furthermore we picked five scientific digital libraries that represent our primary sources for computer science research publications. They are listed in Table 1. Other similar sources were not considered as they mainly index data from the primary sources. We defined (“*Hybrid*”, “*Recommender*”, “*Systems*”) as the basic set of keywords. Then we added synonyms to extend it and obtain the final set of keywords. The set of keywords and synonyms is listed in Table 2. The search string we defined is: (“*Hybrid*” OR “*Hybridization*” OR “*Mixed*”) AND (“*Recommender*” OR “*Recommendation*”) AND (“*System*” OR “*Software*” OR “*Technique*” OR “*Technology*” OR “*Approach*” OR “*Engine*”).

2.2. Selection of papers

Following Step 4 of the protocol, we applied the search string in the search engines of the five digital libraries and found 9673 preliminary primary studies (see Table 4). The digital libraries return different numbers of papers because of the dissimilar filtering settings they use in their search engines. This

Table 4
Number of papers after each selection step

Digital source	Number of papers at the end of step:		
	Search and retrieval	Coarse selection	Detailed selection
SpringerLink	4152	50	13
Scopus	3582	27	9
ACM digital library	1012	53	13
Science direct	484	35	12
IEEEExplore	443	75	29
Total	9673	240	76

Table 5
Quality assessment questions

Quality question	Score	Weight
QQ1. Did the study clearly describe the problems that is addressing?	yes/partly/no (1/0.5/0)	1
QQ2. Did the study review the related work for the problems?	yes/partly/no (1/0.5/0)	0.5
QQ3. Did the study recommend any further research?	yes/partly/no (1/0.5/0)	0.5
QQ4. Did the study describe the components or architecture of the proposed system?	yes/partly/no (1/0.5/0)	1.5
QQ5. Did the study provide an empirical evaluation?	yes/partly/no (1/0.5/0)	1.5
QQ6. Did the study present a clear statement of findings?	yes/partly/no (1/0.5/0)	1

retrieval process was conducted during May 2015. To objectively decide whether to select each preliminary primary study for further processing or not, we defined a set of inclusion/exclusion criteria listed in Table 3. The inclusion/exclusion criteria are considered as a basis of concentrating in the most relevant studies with which to achieve the objectives of the review. Duplicate papers were removed and a coarse selection phase followed. Processing all of them strictly was not practical. Therefore we decided to include journal and conference papers only, leaving out gray literature, workshop presentations or papers that report abstracts or presentation slides. We initially analyzed title, publication year and publication type (journal, conference, workshop, etc.). In many cases abstract or even more parts of each paper were examined for deciding to keep it or not. Our focus in this review work is on hybrid recommender systems. Thus we selected papers presenting mixed or combined RSs dropping out any paper addressing single recommendation strategies or papers not addressing RSs at all. Hybrid RSs represent a somehow newer family of recommender systems compared to other well known and widely used families such as CF or CBF. Therefore the last decade (2005–2015) was considered an appropriate publication period. Using inclusion/exclusion and this coarse selection step we reached to a list of 240 papers. In the next step we performed a more detailed analysis and selection of the papers reviewing abstract and other parts of every paper. Besides relevance based on the inclusion/exclusion criteria, completeness (in terms of problem definition, description of the proposed method/technique/algorithm and evaluation of results) of each study was also taken into account. Finally we reached to our set of 76 included papers. The full list is presented in Appendix together with the publication details.

2.3. Quality assessment

We also defined 6 questions listed in Table 5 for the quality estimation of the selected studies. Each of the question receives score values of 0, 0.5 and 1 which represent answers “no”, “partly” and “yes” correspondingly. The questions we defined do not reflect equal level of importance in the overall quality of the studies. For this reason we decided to weight them with coefficients of 0.5 (low importance) 1 (medium importance) and 1.5 (high importance). We set higher weight to the quality questions that

Table 6
Data extraction form

Extracted data	Explanation	RQ
ID	A unique identifier of the form Pxx we set to each paper	–
Title	–	RQ1
Authors	–	–
Publication year	–	RQ1
Conference year	–	–
Volume	Volume of the journal	–
Location	Location of the conference	–
Source	Digital library from which was retrieved	–
Publisher	–	–
Examiner	Name of person who performed data extraction	–
Participants	Study participants like students, academics, etc.	–
Goals	Work objectives	–
Application domain	Domain in which the study is applied	RQ5
Approach	Hybrid recommendation approach applied	RQ3b
Contribution	Contribution of the research work	–
Dataset	Public dataset used to train and evaluate the algorithm	RQ6c
DM techniques	Data mining techniques used	RQ3a
Evaluation methodology	Methodology used to evaluate the RS	RQ6a
Evaluated characteristic	RS characteristics evaluated	RQ6b
Future work	Suggested future works	RQ7
Hybrid class	Class of hybrid RS	RQ4
Research problem	–	RQ2
Score	Overall weighted quality score	–
Other information	–	–

address the components/architecture of the system/solution (QQ4) and the empirical evaluation (QQ5). Quality questions that address problem description (QQ1) and statement of results (QQ6) got medium importance. We set a low importance weight to the two questions that address the related studies (QQ2) and future work (QQ3). The papers were split in two disjoint subsets. Each subset of papers was evaluated by one of the authors. In cases of indecision the quality score was set after a discussion between the authors. At the end, the final weighted quality score of each study was computed using the following formula:

$$score = \sum_{i=1}^6 w_i * v_i / 6$$

w_i is the weight of question i (0.5, 1, 1.5), v_i is the vote for question i (0, 0.5, 1).

After this evaluation, cross-checking of the assessment was done on arbitrary studies (about 40% of included papers) by the second author. At the end, an agreement on differences was reached by discussion.

2.4. Data extraction

Data extraction was carried on the final set of selected primary studies. We collected both paper meta-data (i.e., author, title, year, etc.) and content data important to answer our research questions like problems, application domains, etc. Table 6 presents our data extraction form. In the first column we list the extracted data, in the second column we provide an explanation for some of the extracted data which may seem unclear and in the third column the research question with which the data is related. All

the extracted information was stored in Nvivo³ which was used to manage data extraction and synthesis process. Nvivo is a data analysis software tool that helps in automating the identification and the labeling of the initial segments of text from the selected studies.

2.5. Synthesis

For the synthesis step we followed Cruzes and Dyba methodology for the thematic synthesis [19]. Their methodology uses the concept of codes which are labeled segments of text to organize and aggregate the extracted information. Following the methodology we defined some initial codes which reflected the research questions. Some examples include the first research problems found, hybrid recommendation classes, first application domains, data mining techniques, recommendation approaches and evaluation methodologies. After completing the reading we had refined or detailed each of the initial codes with more precise sub-codes (leaf nodes in NVivo) which were even closer to the content of the selected papers, covering all the problems found, all the datasets used, and similar detailed data we found. We finished assigning codes to all the highlighted text segments of the papers and then the codes were aggregated in themes (of different levels if necessary) by which the papers were grouped. Afterwards a model of higher-order themes was created to have an overall picture. The research questions were mapped with the corresponding themes. Finally, the extracted data were summarized in categories which are reported in the results section (in pictures or tables) associated with the research questions they belong to.

3. Results

In this section we present the results we found from the selected studies to answer each research question. We illustrate the different categories of problems, techniques, hybridization classes, evaluation methodologies, etc. with examples from the included studies. The results are further discussed in the next section.

3.1. RQ1: Included studies

RQ1 addresses the most relevant studies that present Hybrid RSs. We selected 76 papers as the final ones for further processing. They were published in conference proceedings and journals from 2005 to 2015. The publication year distribution of the papers is presented in Fig. 2. It shows that most of the hybrid RS papers we selected were published in the last 5 years.

For the quality assessment process we used the quality questions listed in Table 5. In Fig. 3, the box plots of quality score distributions per study type (conference or journal) are shown. We see that about 75% of journal studies have quality score higher than 0.9. Same is true for about 35% of conference studies. In Fig. 4 we present the average quality score about each quality question. QQ4 (Did the study describe the components or architecture of the proposed system?) has the highest average score (0.947) whereas QQ3 (Did the study suggest further research?) has the lowest (0.651). The weighted quality score is higher than 0.81 for any included paper. Only one journal study got a weighted average score of 1.0 (highest possible).

³<http://www.qsrinternational.com/products.aspx>.

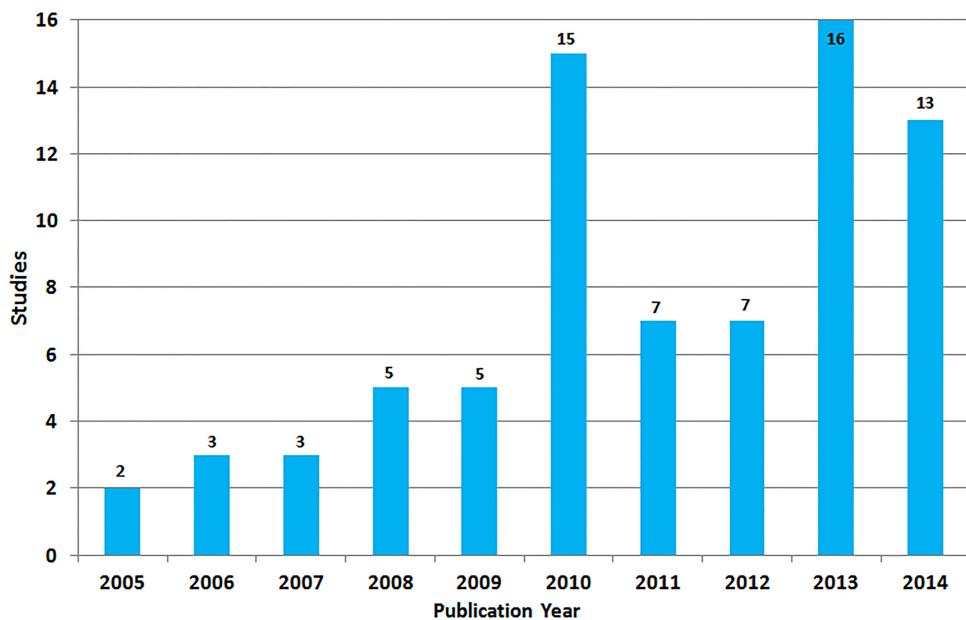


Fig. 2. Distribution of studies per publication year.

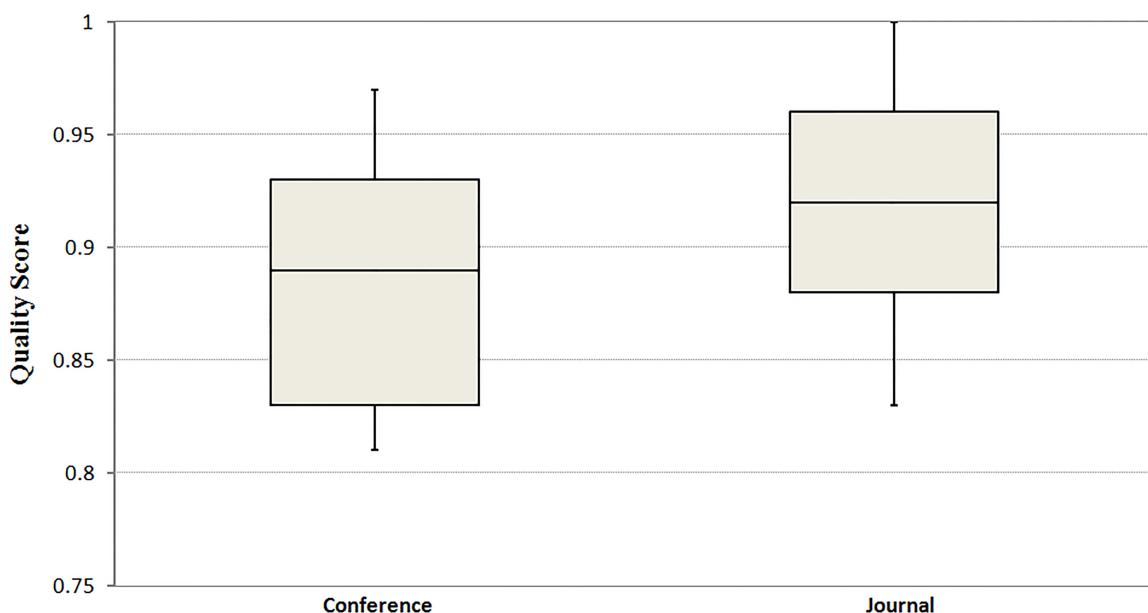


Fig. 3. Boxplot of quality score per publication type.

3.2. RQ2: Research problems

To answer RQ2 we summarize the most important RS problems the studies try to solve. A total of 12 problems were found. The most frequent are presented in Fig. 5 with the corresponding number of studies where they appear. Studies may (and often do) address more than one problem. Same thing

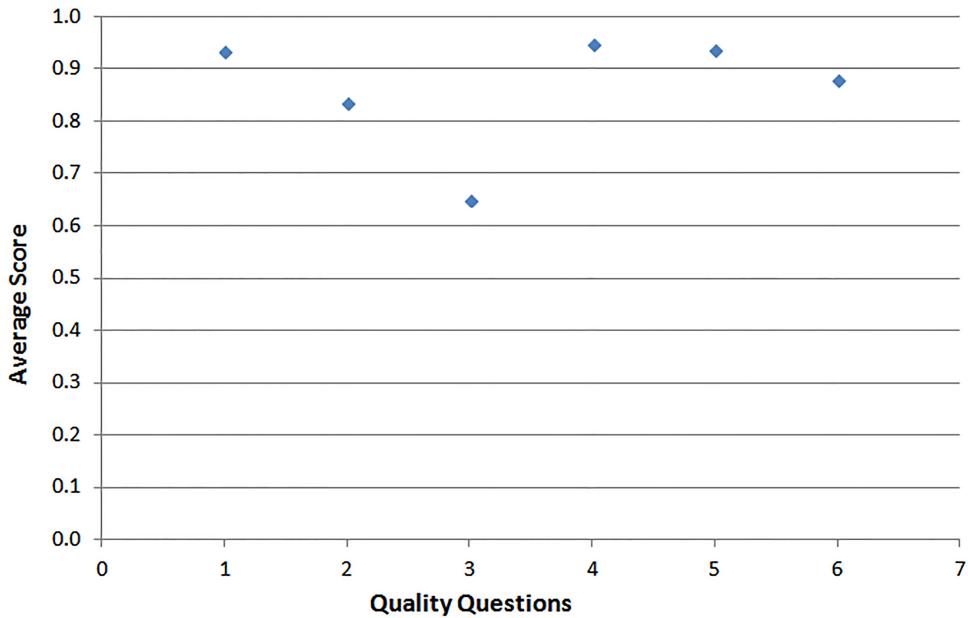


Fig. 4. Average score of each quality question.

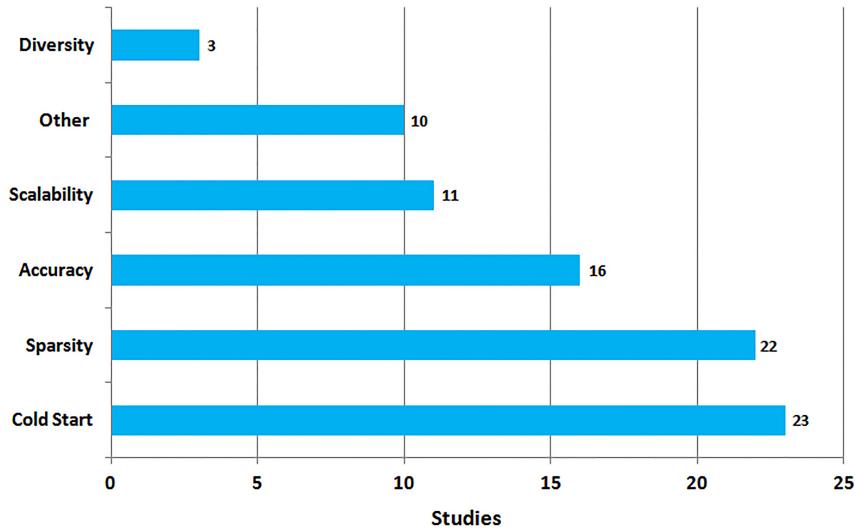


Fig. 5. Addressed problems.

applies for other results (data mining techniques, domains, evaluation metrics, etc.) reported in this section. Below we describe each of the problems:

Cold-start This problem is heavily addressed in the literature [20,21] and has to do with recommendations for new users or items. In the case of new users the system has no information about their preferences and thus fails to recommend anything to them. In the case of new items the system has no ratings for these items and doesn't know to whom recommend them. To alleviate cold-start,

authors in [P21] use a probabilistic model to extract latent features from item's representation. Using the latent features they generate accurate pseudo ratings, even in cold-start situation when few or no ratings are provided. Another example is [P47] where the authors try to solve the new user cold-start in the e-learning domain by combining CF with a CBF representation of learning contents. Cold-start problem is also treated in [P26] where the authors merge the weighted outputs of different recommendation strategies using Ordered Weighted Averaging (OWA), a mathematical technique first introduced in [22]. In total, cold-start was found in 23 studies.

Data sparsity This problem rises from the fact that users usually rate a very limited number of the available items, especially when the catalog is very large. The result is a sparse *user-item* rating matrix with insufficient data for identifying similar users or items, negatively impacting the quality of the recommendations. Data sparsity is prevalent in CF RSs which rely on peer feedback to provide recommendations. In [P13] data sparsity of cross-domain recommendations is solved using a factorization model of the triadic relation *user-item-domain*. Also in [P1] we find an attempt to solve data sparsity by treating each user-item rating as predictor of other missing ratings. They estimate the final ratings by merging ratings of the same item by other users, different item ratings made by the same user and ratings of other similar users on other similar items. Another example is [P5] where CF is combined with Naive Bayes in a switching way. Data sparsity was a research problem of 22 studies.

Accuracy Recommendation accuracy is the ability of a RS to correctly predict the item preferences of each user. Much attention has been paid to improve the recommendation accuracy since the dawn of RSs. Obviously there is still place for recommendation accuracy improvements. This is especially true in data sparsity situations, as accuracy and data sparsity are two problems that appear together in 6 studies (e.g., [P24]). In [P51] a Bayesian network model with user nodes, item nodes, and feature nodes is used to combine CF with CBF and attain better recommendation quality. Other example is [P53] where a web content RS is constructed. The authors construct user's long term interest based on his/her navigation history. Then the similarity of user's profile with website content is computed to decide whether to suggest the website or not. Experiments conducted with news websites show improved accuracy results. Improving accuracy was a research objective of 16 studies.

Scalability This is a difficult to attain characteristic which is related to the number of users and items the system is designed to work for. A system designed to recommend few items to some hundreds of users will probably fail to recommend hundreds of items to millions of people, unless it is designed to be highly scalable. Hyred in [P28] is an example of a system designed to be scalable and overcome data sparsity problem as well. The authors combine a modified Pearson correlation CF with distance-to-boundary CBF. They find the nearest and furthest neighbors of each user to reduce the dataset. The use of this compressed dataset improves scalability, alleviates sparsity, and also slightly reduced the computational time of the system. In [P69] the authors propose a hybrid RS designed to recommend images in social networks. They involve CF and CBF in a weighted way and also consider aesthetic characteristics of images for a better filtering, which overcomes the problem of scalability and cold-start as well. In [P29] a system with better scalability is conceived by combining Naive Bayes and SVM with CF. Improving scalability was addressed in 11 studies.

Diversity This is a desired characteristic that is getting attention recently [23]. Having diverse recommendations is important as it helps to avoid the popularity bias. The latter is having a recommendation list with items very similar to each other (e.g., showing all the episodes of a very popular saga). A user that is not interested in one of them is probably not interested in any of them and gets no value from that recommendation list. *K-Furthest Neighbors*, the inverted neighborhood model of

Table 7
Distribution of studies by DM/ML techniques

DM/ML technique	Studies
K-NN	59
Clustering	34
Association rules	17
Fuzzy logic	14
Matrix manipulation	9
Other	19

K-NN is used in [P12] for the purpose of creating more diverse recommendations. The authors report an increased diversity. However, the user study they conduct shows that the perceived usefulness of it is not different from the one of traditional CF. In [P46] the concept of experts is utilized to find novel and relevant items to recommend. The ratings of users are analyzed and some of the users are promoted as “experts” of a certain taste. They generate recommendations of their for the rest of the “normal” users in that item taste. Diversity is also addressed in [P36] totaling in 3 studies.

Other These are other problems appearing in few studies. They include Lack of Personalization, Privacy Preserving, Noise Reduction, Data source Integration, Lack of Novelty and User preference Adaptiveness.

3.3. RQ3a: Data mining and machine learning techniques

In this section we address the distribution of the studies according to the basic Data Mining (DM) and Machine Learning (ML) techniques they use to build their hybrid RSs. The variety of DM and ML techniques or algorithms used is high. Authors typically use different techniques to build the diverse components of their solutions or prototypes. In Table 7 we present the most frequent that were found in the included studies. Below we describe some of them. More details about the characteristics of DM/ML techniques and how they are utilized to build RSs can be found at [24].

K-NN K-Nearest Neighbors is a well known classification algorithm with several versions and implementations, widely utilized in numerous data mining and other applications. This technique is popular among collaborative filtering RSs which represent the most common family of recommenders. It is mostly utilized to analyze neighborhood and find users of similar profiles or analyze items’ catalog and find items with similar characteristics. K-NN was found in a total of 59 studies.

Clustering There are various clustering algorithms used in RSs and other data mining applications. They typically try to put up a set of categories with which data can be identified. The most popular is *K-means* which partitions the entire data into K clusters. In RSs clustering is mostly applied to preprocess the data. In [P6] the authors experiment with K-way (similar to K-means) clustering and *Bisecting K-means* for grouping different types of learning items. They also use CBF to create learners’ profiles and build an e-learning recommender with improved accuracy. An other example is [P44] where websites are clustered using co-occurrence of pages and the content data of pages. The results are aggregated to get the final recommendations and overcome data sparsity. In total clustering algorithms were used in 34 studies.

Association rules Association rule mining tries to discover valuable relations (association rules) in large databases of data. These associations are in the form $X \Rightarrow Y$, where X and Y are sets of items. The association that are above a minimum level of support with an acceptable level of confidence can be used to derive certain conclusions. In recommender systems this conclusions are of the form

“X likes Y” where X is a user to whom the system can recommend item Y. In [P58] information collected from a discussion group is mined and association rules are used to form the user similarity neighborhood. Word Sense Disambiguation is also used to select the appropriate semantically related concept from posts which are then recommended to the appropriate users of the forum. This hybrid meliorates different problems such as cold-start, data sparsity and scalability. In [P59] classification based on association methods is applied to build a RS in the domain of tourism. The system is more resistant to cold-start and sparsity problems. To overcome cold-start, the authors in [P61] propose a procedure for finding similar items by association rules. Their algorithm considers the user-item matrix as a transaction database where the user Id is the transactional Id. They find the support of each item and keep items with support greater than a threshold. Afterwards, they calculate the confidence of remaining rules and rule scores by which they find the most similar item to any of the items. Association rules were found in 17 studies.

Fuzzy logic Also called *fuzzy set theory* it is a set of mathematical methods that can be used to build hybrid RSs. Those methods are also called reclusive in the literature. Contrary to CF which relies on neighborhood preferences without considering item characteristics, they require some representation of the recommended items [25]. Reclusive methods are complementary to collaborative methods and are often combined with them to form hybrid RSs. An example of using Fuzzy logic is [P27] where better accuracy is achieved by combining 2 CFs with a fuzzy inference system in a weighted way to recommend leaning web resources. In [P34] fuzzy clustering is used to integrate user profiles retrieved by a CF with Point Of Interest (POI) data retrieved from a context aware recommender. The system is used in the domain of tourism and provides improved accuracy. In total Fuzzy logic was found in 14 studies.

Matrix manipulation Here we put together the different methods and algorithms that are based on matrix operations. The methods we identified are Singular Value Decomposition (SVD), Latent Dirichlet Allocation (LDA), Principal Component Analysis (PCA), Dimensionality Reduction and similar matrix factorization techniques. Matrix manipulation methods are often used to build low error collaborative RSs and were especially promoted after the Netflix challenge was launched in 2006. In [P75] a topic model based on LDA is used to learn the probability that a user rates an item. An other example is [P76] where Dimensionality Reduction is used to solve sparsity and scalability in a multi-criteria CF. They were found in 9 studies.

Other Other less frequent techniques such as Genetic Algorithms, Naive Bayes, Neural Networks, Notion of Experts, Statistical Modeling, etc. were found in 19 papers.

3.4. RQ3b: Recommendation technique combinations

In this section we present a list of the most common technique combinations that form hybrid RSs. We also present the problems each of this combinations is most frequently associated with. In the following subsections the construct and technical details of some of the prototypes implementing each combination is described. Table 8 presents the summarized results.

3.4.1. CF-X

Here we report studies that combine CF with one other technique which is not CBF (those are counted as CF-CBF). An example of this combination is [P8] where the authors go hybrid to improve the performance of a multi-criteria recommender. They base their solution on the assumption that usually only a few selection criteria are the ones which impact user preferences about items and their corresponding ratings. Clustering is used first to group users based on the items' criteria they prefer. CF is then used

Table 8
Hybrid recommendation approaches distributed per problem

Problem	Hybrid recommenders and studies					
	CF-X	CF-CBF	CF-CBF-X	IICF-UUCF	CBF-X	Other
Cold-start	2	3	2	1	1	5
Data sparsity	0	5	3	3	4	6
Accuracy	2	3	0	2	2	4
Scalability	0	2	2	0	2	2
Diversity	2	0	0	0	0	1
Other	0	2	1	1	1	2
Total	6	15	8	7	10	20

within each cluster of similar users to predict the ratings. They illustrate their method by recommending hotels from TripAdvisor⁴ and report performance improvements over traditional CF. Other attempt to improve the predictive accuracy of traditional CF is [P60]. Here the authors integrate in CF discrete demographic data about the users such as *gender*, *age*, *occupation*, etc. Fuzzy logic is used to compute similarities between users utilizing this extra demographic data and integrate the extra similarities with the user-based similarities calculated from ratings history. After calculating the final user similarities their algorithm predicts the rating values. The extra performance which is gained from the better user similarities that are obtained, comes at the cost of a slightly larger computational time which is however acceptable. In total CF-X combination was found in 6 studies with X being KBF, DF or a DM/ML technique from those listed in Table 6.

3.4.2. CF-CBF

This is a very popular hybrid RS utilizing the two most successful recommendation strategies. In many cases the recommendations of both systems are weighted to produce the final list of predictions. In other cases the hybrid RS switches from CF to CBF or is made up of a more complex type of combination (see Section 3.5). An example is [P28] where the authors develop a hybrid RS suitable for working with high volumes of data and solve scalability problems in e-commerce systems. Their solution first involves CF (Pearson's product moment coefficients) to reduce the dataset by finding the nearest neighbors of each user, discarding the rest and reducing the dataset. Afterwards distance-to-boundary CBF is used to define the decision boundary of items purchased by the target user. The final step combines the CF score (correlation coefficient between two customers) with the distance-to-boundary score (distance between the decision boundary and each item) in a weighted linear form. The authors report an improved accuracy of their hybrid RS working in the reduced dataset, compared to other existing algorithms that use full datasets.

In [P51] the authors propose a CF-CBF hybrid recommender which is based on Bayesian networks. This model they build uses probabilistic reasoning to compute the probability distribution over the expected rating. The weight of each recommending strategy (CF and CBF) is automatically selected, adapting the model to the specific conditions of the problem (it can be applied to various domains). The authors demonstrate that their combination of CF and CBF improves the recommendation accuracy. Other studies involve similar mathematical models or constructs (e.g., fuzzy logic) to put together CF and CBF and gain performance or other benefits. In total CF-CBF contributions were found in 15 studies.

⁴<http://www.tripadvisor.co.uk>.

3.4.3. CF-CBF-X

Those are cases in which CF and CBF are combined together with a third approach. One example is [P14] where CF and CBF are combined with DF to generate recommendations for groups of similar profiles (users). These kind of recommendations are particularly useful in online social networks (e.g., for advertising). The goal of the authors is to provide good recommendations in data sparsity situations. First CBF is used to analyse ratings and items' attributes. CF is then invoked as the second stage of the cascade to generate the group recommendations. DF is used to reinforce CF in the cases of sparse profiles (users with few ratings). In total CF-CBF-X was found in 8 studies. X is mostly a clustering technique or DF.

3.4.4. IICF-UUCF

Item-Item CF and User-User CF are two forms of CF recommenders, differing on the way the neighborhoods are formed. Some studies combine both of them to improve overall CF performance. An example is [P70] where the authors present a hybrid recommendation framework they call Collaborative Filtering Topic Model (CFTM) which considers both user's reviews and ratings about items of a certain topic (or domain) in e-commerce. The first stage which is offline performs sentiment analysis in the reviews to calculate the User or Item similarity. The second stage of the cascade uses IICF or UUCF (switching) to predict the ratings. The authors evaluate using 6 datasets of different domains from Amazon and report that their hybrid approach performs better than traditional CF, especially in sparsity situations. IICF-UUCF combinations were found in 7 studies.

3.4.5. CBF-X

There were also 10 studies in which CBF is combined with another technique X which is not CF (counted as CF-CBF). X represents different approaches like KBF and DF or DM/ML techniques like clustering etc. One example is [P63] where the authors describe and use the interesting notion of *user lifestyle*. They select demographic information, consumer credit data and TV program preferences as lifestyle indicators, and confirm their significance by performing statistical analysis on 502 users. The most significant lifestyle attributes are binary encoded and used to form the neighborhoods and ratings of each user by means of Pearson correlation. The authors call the resulting complete (in terms of ratings) matrix *pseudoUser-item* matrix. It is then used for a Pearson based (classical CF) prediction of the original *user-item* ratings. Considerable performance improvements are reported.

3.4.6. Other

Other implementations include combinations of the same recommendation strategy (e.g., *CF1-CF2* with different similarity measures or tuning parameters each), trust-aware recommenders that are being used in social communities, prototypes using association rules mining, neural networks, genetic algorithms, dimensionality reduction, social tagging, semantic ontologies, pattern mining or different machine learning classifiers.

3.5. RQ4: Classes of hybridization

To answer RQ4 we classified the examined hybrid RSs according to the taxonomy proposed by Burke [12]. This taxonomy categorizes hybrid RSs in 7 classes based on the way the different recommendations techniques are aggregated with each other. Each class is explained in the subsections below where we discuss in more details few examples from the included papers. The results are summarized in Fig. 6.

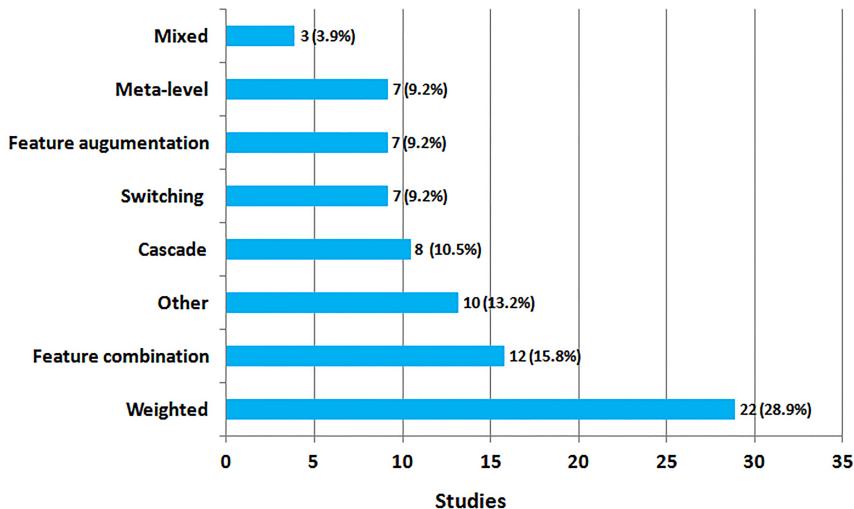


Fig. 6. Distribution of studies per hybridization class.

3.5.1. Weighted

Weighted hybrids were the most frequent. They compute the scores of the items they recommend by aggregating the output scores of each recommendation technique using weighted linear functions. One of the first weighted recommenders was P-Tango [26] which combined CF and CBF rating scores in a linear weighted way to recommend online newspapers. In P-Tango, aggregation was made giving equal initial weights to each score and then possibly adapting by the feedback of users. The weights of CF and CBF are set on a per-user basis enabling the system to determine the optimal mix for each user and alleviating the “gray sheep” problem. In [P38] the authors propose a weighting method for combining user-user, user-tag and user-item CF relations in social media. The method they propose computes the final rating score of an item for a user as the linear combination of the above three CF relations. Unlike the traditional CF, this weighted hybrid CF recommender is completely based on tags and does not require that users provide explicit rating scores for the items that are recommended (e.g., photos). An other example is [P6] where the authors combine a content-based model with a rule-based model to recommend e-learning materials. They build their CBF using an education domain ontology and compute the scores of each learning material using *Vector Space Model* and *TF-IDF*. The rule-based recommender utilizes the ontology and the user’s previously visited concepts to realize a semantic mapping between user’s query and his/her semantic profile, resulting in adequate term recommendations about learning materials. The two RS modules set different weights to each recommended item based on user’s preferences and higher accuracy is achieved. Apparently the benefit of a weighted hybrid is the fact that it uses a straightforward way to combine the results of each involved technique. It is also easy to adjust priority assignment for each involved strategy by changing the weights. This class of hybrid RS was used in 22 (28.9%) of the included studies.

3.5.2. Feature combination

This type of hybrid RSs treats one recommender’s output as additional feature data, and uses the other recommender (usually content-based which makes extensive use of item features) over the new extended data. In case of a CF-CBF hybrid, the system does not exclusively rely on the collaborative data output of CF. That output is considered as additional data for the CBF which generates the final list. This reduces

the sensitivity to possible sparsity of the initial data. For example, in [P40] the authors present a CF-CBF book recommender which implements an extended feature combination strategy. In the first phase new features (preferred books) are generated by applying CF among the readers. In the second phase they utilize *fuzzy c-means clustering* and *type-2 fuzzy logic* to obtain data for creating book categories of each user type (teacher, researcher, student). In the third and final phase CBF is involved to recommend the most relevant books to each user. The authors report performance improvements both in MAE and F1 accuracy scores. Also in [P25] the authors build an information system about courses and study materials for scholars. The system invokes a web crawler to collect related web pages and classifies the obtained results in different item categories (websites, courses, academic activities) using a web page classifier supported by a school ontology. An information extractor is later invoked to get significant web page features. Finally the system operates on the extra features of each item category to produce integrated recommendations based on the order of the keyword weight of each item. System verification reports higher recommendation quality and reliability. Feature combination hybrids were found in 12 (15.8%) studies.

3.5.3. Cascade

Cascade hybrids are examples of a staged recommendation process. First one technique is employed to generate a coarse ranking of candidate items and than a second technique refines the list from the preliminary candidate set. Cascades are order-sensitive; a CF-CBF would certainly produce different results from a CBF-CF. An example is [P67] which presents a mobile music cascade recommender combining SVM genre classification with collaborative user personality diagnosis. The first level of the recommendation process consists of a multi-class SVM classifier of songs based on their genre. The second level is a personality diagnosis which assumes that user preferences for songs constitute a characterization of their underlying personality. The personality type of each user is assumed to be the vector of ratings in the items the user has seen. The personality diagnosis approach estimates the probability that each active user is of the same personality type as other users. As a result the probability that a active user will like new songs is computed in a more personalized way.

In [P49] the authors combine two CF systems with different properties. The first module is responsible for retrieving the data and generating the list of neighbors for each user. This module uses two distance measures, Pearson's coefficient and Euclidean distance in a switching way, depending on the user's deviation from his/her average rating. The authors report that Euclidean distance performs better than Pearson's coefficient in most of the cases. In the second module of the cascade, they experiment switching between three predictors to generate the final recommendations: Bayesian estimator, Pearson's weighted sum and adjusted weighted sum. They also report that the Bayesian prediction gives best results. An other example of a cascade hybrid is [P68]. It implements a cascade of item-based CF and Sequential Pattern Mining (SPM) to recommend items in an e-learning environment. To adopt the CF to the e-learning domain they introduce a damping function which decreases the importance of "old" ratings. The SPM module takes in a list of k most similar items for each item and determines its support. At the end it prunes the items with support less than the threshold and generates the recommended items. The authors also apply this recommender in P2P learning environments for resource pre-fetching. Cascade hybrids were found in 8 (10.5%) studies.

3.5.4. Switching

In a switching hybrid the system switches between different recommendation techniques according to some criteria. For example, a CF-CBF approach can switch to the content-based recommender only

when the collaborative strategy doesn't provide enough credible recommendations. Even different versions of the same basic strategy (e.g., CBF1-CBF2 or CF1-CF2) can be integrated in a switching form. An example is DailyLearner, an online news recommender presented in [27]. It first employs a short-term CBF recommender which considers the recently rated news stories utilizing *Nearest Neighbor* text classification and *Vector Space Model* with *TF-IDF* weights. If a new story has no near neighbors the system switches to the long-term model which is based on data collected over a longer time period, presenting user's general preferences. It uses a Naive Bayes classifier to estimate the probability of news being important or not.

In [P29] the authors build a switching hybrid RS that is based on a Naive Bayes classifier and Item-Item CF. The classifier is trained in offline phase and used to generate the recommendations. If these recommendations have poor confidence the Item-Item CF recommendations are used instead. First, they compute the posterior probability of each class generated by the Naive Bayes classifier. Then they assume that the classifier's confidence is high if the posterior probability of the predicted class is sufficiently higher than the ones of the other classes. MovieLens and FilmTrust are employed to evaluate the approach and performance improvements are reported, both in accuracy and in coverage. An other example of a switching hybrid is [P55] where the authors describe the design and implementation of a mobile location-aware CF-KBF recommender of touristic sites (e.g., restaurants). Their system involves both CF and KBF modules in generating recommendations. Then 3D-GIS location data are used to compute the physical distance of the mobile user from the recommended sites. The system switches from one recommendation strategy to the other and performs a distance-based re-ranking of the recommendations, choosing the sites that are physically closer to the user with higher accuracy. In most of the cases we see that complexity of switching RSs lies in the switching criteria which are mostly based on distance or similarity measures. However, these systems are sensitive to the strengths and weaknesses of the composing techniques. This hybrid RS category was found in 7 (9.2%) studies.

3.5.5. Feature augmentation

In this class of hybrids, one of the combined techniques is used to produce an item prediction or classification which is then comprised in the operation of the other recommendation technique. Feature augmentation hybrids are order-sensitive as the second technique is based on the output of the first. For example an association rules engine can generate for any item, similar items which can be used as augmented item attributes inside a second recommender to improve its recommendations. Libra presented in [28] is a content-based book recommender. It augments the textual features of the books with "related authors" and "related titles" data obtained from Amazon CF recommender to obtain a better recommendation quality. Libra uses an inductive learner to create user profiles. This inductive learner is based on vectorized bag-of-words naive Bayes text classifier. The authors report that the integrated collaborative content has a significant positive effect on recommendation performance.

[P36] presents a hybrid method which combines multidimensional clustering and CF to increase recommendation diversity. They first invoke multidimensional clustering to collect and cluster user and item data. Clusters with similar features are deleted and the remaining feature clusters are fed into the CF module. Item-Item similarity is computed using an adjusted cosine similarity which works for m cluster features of each item. Finally the rating predictions are computed base on item-item similarity and the rating deviations from neighbors. The authors report an increase in recommendation diversity with only minimal loss in accuracy. Feature augmentation offers a means of improving the performance of a system (in the above examples the second recommender) without the need to modify it. The extra functionality is added by augmenting the processed data. This hybrid RS class was used in 7 (9.2%) studies.

3.5.6. Meta level

Meta levels are also an example of order-sensitive hybrid RSs that use an entire model produced by the first technique as input for the second technique. It is typical to use content-based recommenders to build item representation models, and then employ this models in collaborative recommenders to match the items with user profiles. A meta level recommendation strategy was implemented by Fab [10], one of the first website recommenders. Fab uses a selection agent which based on *term vector model* accumulate user-specific feedback about areas of interest for each user. There are also two collection agents: search agents which perform a search for websites, and index agents which construct queries for already found websites to avoid duplicate work. Collection agents utilize the models of the users (collaborative component) to collect the most relevant websites which are then recommended to the users.

Also [P20] presents a meta level recommender used in the domain of music which integrates CF with CBF. Here each user is stochastically matched with a music genre based on the collaborative output. Then the system generates a musical piece for the user based on the acoustic features. For the integration they adopt a probabilistic generative model called *three-way aspect model*. As this model is only used for textual analysis and indexing (bag-of-words representation) they propose the *bag-of-timbres* model, an interesting approach to content-based music recommendations which represents each musical piece as a set of polyphonic timbres. The advantage this hybridization class presents is that the learned model of the first technique is compressed and thus better used from the second. However, the integration effort is considerable and use of advanced constructs is often required. This hybrid RS class was found in 7 (9.2%) studies.

3.5.7. Mixed

Mixed hybrids represent the simplest form of hybridization and are reasonable when it is possible to put together a high number of different recommenders simultaneously. Here the generated item lists of each technique are added to produce a final list of recommended items. One of the first examples of mixed hybrids was PTV system [29] which used CBF to relate similar programs to the user profile and CF to relate similar user profiles together. The CBF module converts each user profile in a feature-based representation they call *profile schema* which is basically a TV program content summary represented in features. The CF module computes the similarity of two users utilizing a graded difference metric of the ranked TV programs in each user's profile. At the end, a selection of programs recommended by the two modules is suggested.

Yet another example of recommending TV programs is a CF-CBF mixed hybrid named queveo.tv described in [P52]. Here the authors use demographic information such as age, gender and profession together with user's history to build his/her profile which is used by the CBF module. This module makes use of Vector Space Model and cosine correlation to provide the recommended TV programs. The CF module uses both user-based CF to generate the top neighbors of the active user, and item-based CF to predict the level of interest of the user for a certain item. At the end the system takes recommendations from the two modules to generates the final list of TV programs. Those TV programs that were part of both listings (CBF and CF) are highlighted as *Star Recommendations*, as they are probably the most interesting for the user. Mixed hybrid RSs are simple and can eliminate acute problems like cold-start (new user or new item). They were found in 3 (3.9%) studies only.

3.6. RQ5: Application domains

A rich collection of 18 application domains was identified. Figure 7 presents the percentage of studies for each application domain. We see that most of the studies (21 or 27.6%) are domain independent.

Table 9
Evaluation methodology

Methodology	Studies
Comparison with similar method	58
User survey	14
Comparison and user survey	3
No evaluation	1

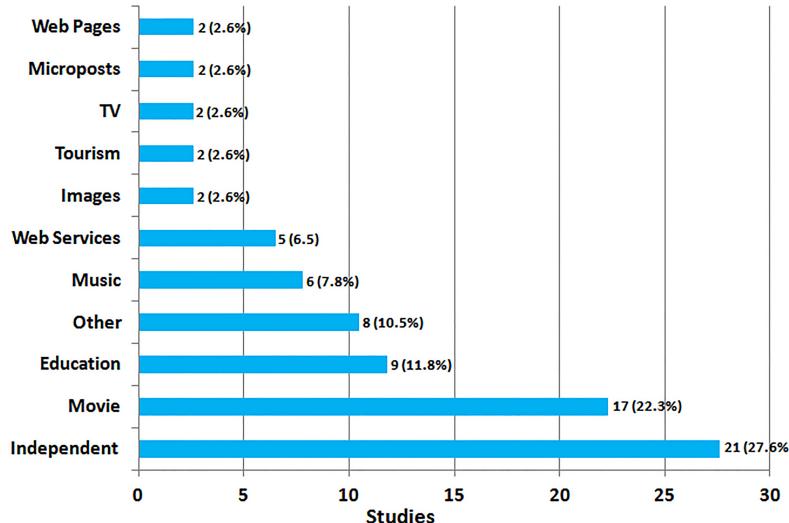


Fig. 7. Distribution of studies according to the application domains.

They haven't been applied to a particular domain. Movie domain was considered by 17 (22.3%) studies. Next comes education or e-learning considered by 9 (11.8%) studies. Six (7.8%) studies were applied in the domain of music. There were also web service RSs implemented in 5 (6.5%) studies. Other domains are images, touristic sites, TV programs, web pages and microposts which appeared in 2 (2.6%) studies each. Domains like business, food, news, bibliography, etc. categorized as "Other" count for less than 10.5% of the total number of studies.

3.7. RQ6: Evaluation

Another important aspect of hybrid RSs that we examined is the evaluation process. In this section we present results about the evaluation methodologies and the corresponding involved metrics (answering RQ6a), evaluated RS characteristics and the utilized metrics for each (answering RQ6b) and finally the public datasets used to train and test the algorithms (answering RQ6c).

3.7.1. RQ6a: Evaluation methodologies

Here we try to explain how (with what methodologies) the evaluation process is performed and what metrics are involved in each methodology. Table 9 lists the distribution of studies according to the methodology they use to perform the evaluation. There are 58 (more than three-quarters) studies comparing the proposed system (or solution) with a similar well known method or technique. Usually CF-X or CF-CBF hybrid RSs are compared with pure CF or CBF. In some cases the proposed system is compared with different parameter configurations of itself. Accuracy or error measures like MAE (Mean

Table 10
Evaluated characteristics

Recommendation characteristic	Studies
Accuracy	62
User satisfaction	10
Diversity	7
Computational complexity	6
Novelty-Serendipity	4

Average Error) or RMSE (Root Mean Square Error) are very common. They estimate the divergence of the RS predictions from the actual ratings. Decision support metrics like Precision, Recall and F1 are also very frequent. Precision is the percentage of selected items that are relevant. Recall is the percentage of relevant items that are recommended. F1 is the harmonic mean of the two. User surveys are the other evaluation methodology utilized in 14 studies. They mainly perform subjective quality assessment of the RS and require the involvement of users who provide feedback for their perception about the system. Surveys are usually question based and reflect the opinion of users about different aspects of the hybrid recommender. An example of user surveys is [P27] where the participants were 30 high school students. In [P50] the users of the survey are customers of a web retail store who rated products they purchased. In [P74] a mix of real and simulated users are used to rate movies, books, etc. In total user surveys were conducted in 14 studies.

Both comparisons and surveys are used in 3 studies: [P9] where the participants were 17 males along with 15 females and different versions of the system were compared with each-other, [P12] where the system was compared with CF using MovieLens and the survey involved 132 participants, and [P40] where online user profiles were utilized for the survey, and the proposed fuzzy hybrid book RS was compared with traditional CF. The only study with no evaluation at all was [P23]. Here the authors present a personalized hybrid recommendation framework which integrates trust-based filtering with multi-criteria CF. This framework is specifically designed for various Government-to-Business e-service recommendations. The authors leave the evaluation of their framework as a future work.

3.7.2. RQ6b: Characteristics and metrics

In order to address RQ6b we analyzed the recommendation characteristics the authors evaluate, and what metrics they utilize. Five characteristics were identified, listed in Table 10. The top characteristic is accuracy measured in 62 studies. It is followed by user satisfaction, a subjective characteristic assessed in 10 studies. Diversity is about having different list of recommended items each time the user interacts with the system. In total it was measured in 7 studies. Computational complexity of the RS is measured in 6 studies. Novelty and serendipity express the capability of the hybrid RS to recommend new or even unexpected but still relevant items to the user. They were measured in 4 studies. We also observed the metrics that authors use for each evaluated characteristic, summarized in Table 11. Accuracy is mostly measured by means of precision (31 studies), recall (23) and F1 (14). MAE and RMSE were found in 27 and 6 studies correspondingly. Other less frequent metrics used to evaluate accuracy include MSE (Mean Squared Error), nDCG (normalized Discounted Cumulative Gain), AUC, etc. They were found in 15 studies. As previously mentioned user satisfaction is measured by means of user surveys which were found in 10 studies. They usually consist of polls which aim to get the opinion of the users about different recommendation aspects of the system. Diversity is measured mostly by coverage which was found in 4 studies. In the other cases it is measured using ranking distances (3 studies). Execution time is the time it takes for the system to provide the recommendations and is a measure of the computational complexity. It was found in 6 studies. Novelty and Serendipity are measured by less known metrics such as Surprisal, Coverage in Long-Tail or Expected Popularity Complement.

Table 11
Evaluated characteristics and involved metrics

Characteristic	Metrics	Studies
Accuracy	Precision	31
	MAE	27
	Recall	23
	F1	14
	RMSE	6
	Other	15
User satisfaction	Qualitative Subjective Assessment	10
Diversity	Coverage	4
	Ranking distances	3
Complexity	Execution time	6
Novelty-Serendipity	Surprisal	2
	Coverage in Long-Tail	1
	Expected Popularity Complement	1

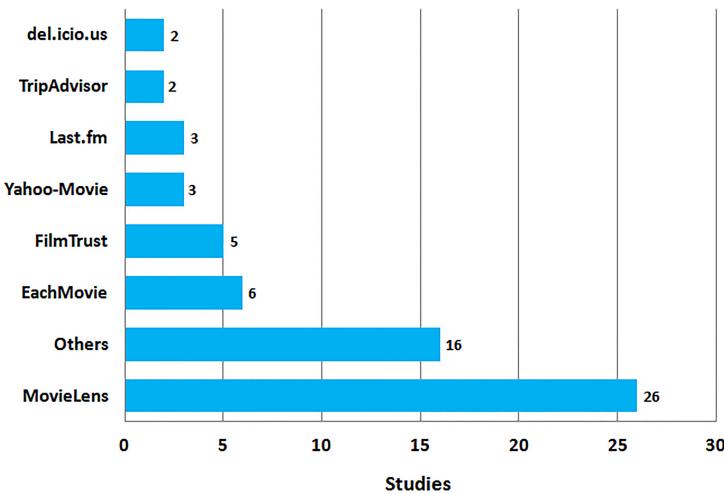


Fig. 8. Distribution of studies according to the datasets they use for evaluation.

3.7.3. RQ6c: Datasets

We also kept track of the public datasets used by the authors to evaluate their hybrid RSs. These datasets are used by the scientific community to replicate experiments and validate or improve their techniques. There are 55 studies that use at least one public dataset. Sometimes a study uses more than one dataset. On the other hand 21 studies do not use any dataset. Sometimes they use synthetic data or rely on user surveys or other techniques. In Fig. 8 we present the datasets that were used and the number of studies in which they appear.

MovieLens⁵ used in 26 studies, is one of the most popular public datasets used in the field of RSs. It was collected and made available by GroupLens⁶ which is still maintaining it.

⁵ <http://grouplens.org/node/73>.

⁶ <http://grouplens.org>.

Table 12
Future work suggestions

Future work	Studies
Extend the proposed solution	14
Perform better evaluation	11
Other	9
Add context to recommendations	8
Consider other application domains	7
Use more data or item features	7
Experiment with more or different algorithms	6
Try other hybrid recommendation class	5

EachMovie is also a movie dataset used in 6 studies. Even though it is now retired, it was the original basis for MovieLens and has been extensively used by the RS community.

FilmTrust is a movie dataset and a recommendation website that uses the concept of trust to recommend movies. It is smaller in size compared to the other movie datasets but it has the advantage of being more recent in content. FilmTrust was used in 5 studies.

Yahoo-Movie is a dataset containing a subset of Yahoo Movie community preferences for movies. It also contains descriptive information about many movies released prior to November 2003. Yahoo-Movie was used in 3 studies.

Last.fm⁷ is a music dataset crawled by last.fm website. It contains information about some of the users' attributes, their track preferences and the artists. Last.fm was used in 3 studies.

Tripadvisor is a dataset consisting of hotel and site reviews crawled by tripadvisor website. It is especially used to provide touristic recommendations to mobile users. Tripadvisor was used in 2 studies.

Delicious⁸ is a dataset containing website bookmarks and tags of the form (user, tag, bookmark) shared by many users within the network. Delicious dataset was used in 2 studies.

Other less popular datasets containing different type of recommendable items were found in 16 studies.

3.8. RQ7: Future work

The last research question has to do with future work opportunities and directions. Our findings are summarized in Table 12 and shortly explained below:

Extend the proposed solution It is a common suggestion stated by many authors. They often identify and suggest several additional parts or components which could be aggregated to the system to improve the performance, extend the functionalities, etc. It is suggested in 14 (18.4%) studies.

Perform better evaluation It is difficult to evaluate recommender systems. The hard part is to find the most appropriate techniques or algorithms that can be used as benchmark. Performing a good evaluation of the proposed system increases its value and credibility. This suggestion appears in 11 (14.4%) studies.

Add context to recommendations The authors suggest to make more use of contextual (location, time of day, etc.) data which are revealed by mobile users. It appears in 8 (10.5%) studies.

⁷ <http://ocelma.net/MusicRecommendationDataset/lastfm-360K.html>.

⁸ <http://disi.unitn.it/~knowdive/dataset/delicious/>.

Consider other application domains Some of the studies apply their contributions in a certain domain. Different authors target alternative domains or propose domain independent contributions. Considering other domains was suggested in 7 (9.2%) studies.

Use more data or item features Some authors plan to use more data for training their algorithms or plan to extract and use more features of the recommended items. This has been stated in 7 (9.2%) studies.

Experiment with more or different algorithms Some authors suggest to combine different recommendation or data mining algorithms and see the results they can obtain. Sometimes they suggest to use alternative similarity measures also. This has been suggested in 6 (7.9%) studies.

Try other hybridization class Although it is not always possible, combining the applied techniques in another way could bring better results. Trying another hybridization class appeared in 5 (6.5%) studies.

Other Other future work suggestions include applying hybrid RSs in less frequent domains or contexts, making more personalized recommendations, reducing the computational cost of the solution, improving other recommendation quality criteria (besides accuracy) like diversity or serendipity, etc.

4. Discussion

The main issues covered in this work are presented in the schematic model of Fig. 9. The issues are associated with the research question they belong to. In this section we discuss the obtained results for each research question.

4.1. Selected studies

The quality evaluation results of the selected studies are presented in Figs 3 and 4. These results indicate that journal studies have lower spread and slightly higher quality score than conference studies. The authors in [30], a systematic review work about linked data-based recommender systems, report similar results. Regarding the publication year of the selected studies, we see in Fig. 2 a steady increase in hybrid RS publications. More than 76% of the included papers were published in the second half (from 2010 later on) of the 10 years time period. This high number of recent publications suggest that hybrid RSs are still a hot topic. As mentioned in introduction, similar increased academic interest in RSs is also reported by other surveys like [14] or [15]. Some factors that have boosted the publications and development of RSs are probably the Netflix Prize⁹ (2006–2009) and the boom of social networks.

4.2. Problems and challenges

Cold-start was the most acute problem that was found. CF RSs are the most affected by cold-start as they generate recommendations relying on ratings only. Hybrid RSs try to overcome the lack of ratings by combining CF or other recommendation techniques with association rule mining or other mathematical constructs which extract and use features from items. Data sparsity is also a very frequent problem in the field of RSs. It represents a recommendation quality degradation due to the insufficient number of ratings. Hybrid approaches try to solve it by combining several matrix manipulation techniques with the

⁹<http://www.netflixprize.com/>.

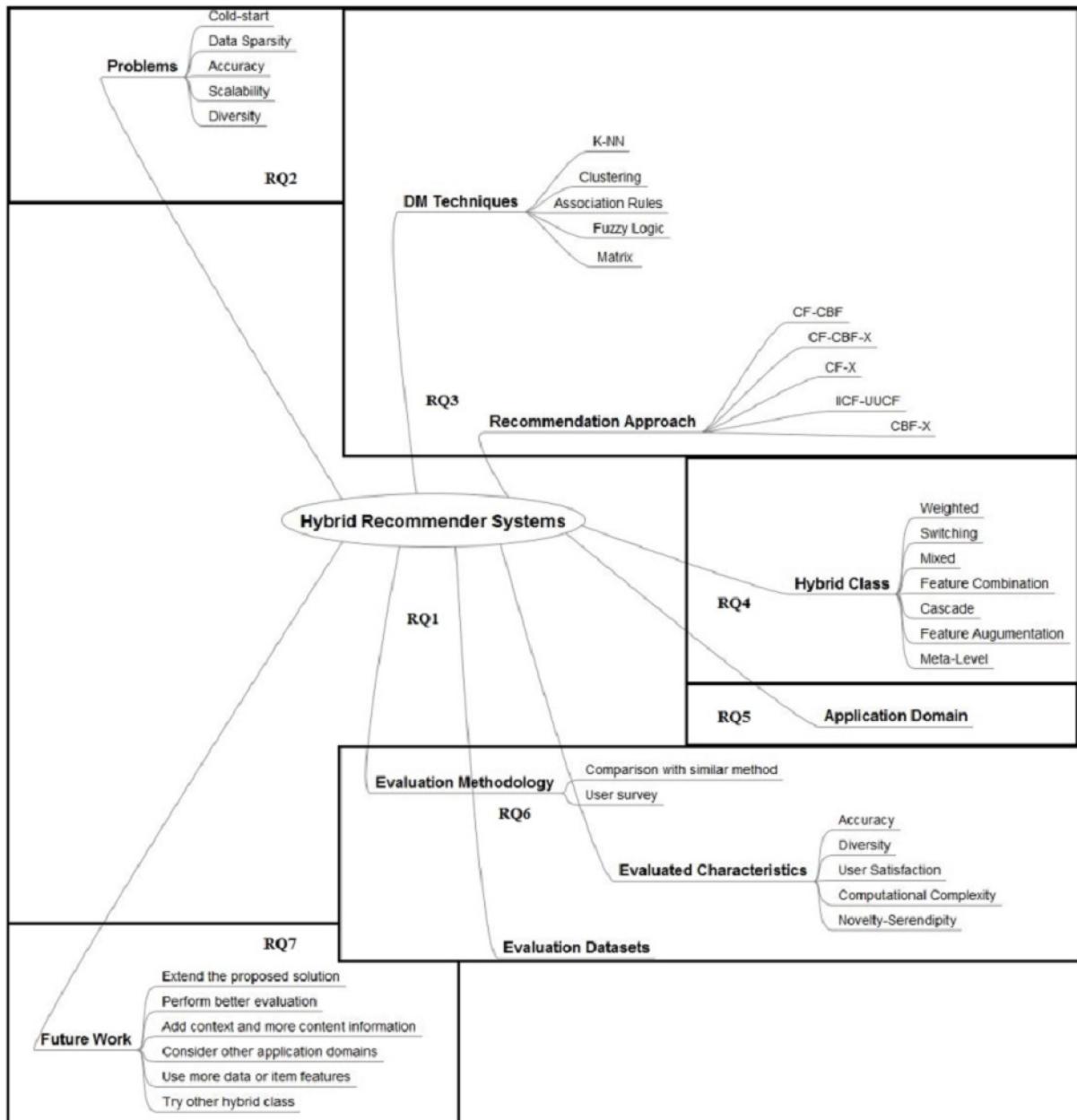


Fig. 9. RQs and higher-order themes.

basic recommendation strategies. They also try to make more use of item features, item reviews, user demographic data or other known user characteristics.

Accuracy has been the top desired characteristic of RSs since their dawn, as it directly influences user satisfaction. Improving recommendation accuracy is a problem that is mostly addressed by using parallel (i.e. in a weighted or switching hybrid classes) recommendation techniques. Scalability is also an important problem which is frequently found in association with data sparsity (appear together in

Table 13
Problems and possible solutions

Problems	Possible solutions	References
Cold-Start	Use association rule mining on item or user data to find relations which can compensate the lack of ratings. Mathematical constructs for feature extraction and combination of different strategies can also be used.	[P21], [P61], [P26], [P58], [P59]
Sparsity	Use the few existing ratings or certain item features to generate extra pseudo ratings. Experiment with Matrix Factorization or Dimensionality Reduction.	[P1], [P44], [P76], [P13]
Accuracy	Use Fuzzy Logic or Fuzzy Clustering in association with CF. Try putting together CF with CBF using Probabilistic Models, Bayesian Networks or other mathematical constructs.	[P27], [P34], [P6], [P40], [P20], [P51]
Scalability	Try to compress or reduce the datasets with Clustering or different measures of similarity.	[P28], [P76], [P28]
Diversity	Try modifying neighborhood creation by relaxing similarity (possible loss in accuracy) or use the concept of experts for certain item tastes.	[P36], [P46], [P12]

9 studies). Lack of diversity is a problem that has been addressed in few studies. As explained in [31] diversity is frequently in contradiction with accuracy. Authors usually attain higher diversity by tolerable relaxations in accuracy. In general we see that hybrid RSs try to solve the most acute problems that RSs face. In Table 13 we summarize some typical solutions about each problem with examples from papers discussed in Sections 3.2–3.5.

4.3. Techniques and combinations

As shown in Table 7, K-NN is the most popular DM technique among hybrid RSs. This result highlights the fact that K-NN CF is one of the most successful and widespread RSs. Clustering techniques are also commonly used. There are different types of clustering algorithms with *K-means* being the most popular. Clustering as a process is mostly involved in preliminary phases to identify similar users, similar items, similar item features, etc. Association rules are also used to identify frequent relations between users and items. Fuzzy logic and matrix manipulation methods are also incorporated in hybrid RSs. In most of the cases authors combine 2 recommendation strategies. In few cases even 3 are involved. CF-CBF is the most popular combination, commonly associated with recurrent problems like data sparsity, cold-start and accuracy. CF-CBF-X is also common. Here CF and CBF are combined together and reinforced by a third technique.

In CF-X combinations, X is usually integrated in CF to improve its performance and usually represents fuzzy logic (reclusive methods are complementary to collaborative methods) or clustering. IICF-UUCF is also popular as it represents the combination of two basic versions of CF. In conclusion, as can be inferred from Table 8, the most common recommendation techniques (with CF being the most popular) are combined to solve the typical problems which are cold-start, data sparsity and accuracy. Actually it is not a surprise that CF combines with almost any other recommendation technique. Other surveys report similar results. In [32] the authors present a broad survey about CF techniques. They also conclude that most of hybrid CF recommenders use CF methods in combination with content-based methods (CF-CBF is also the most frequent combination we found) or other methods to fix problems of either recommendation technique and to improve recommendation performance. CBF-X addresses problems like data sparsity, accuracy and scalability.

Other combinations put together techniques like Bayesian methods, demographic filtering, neural networks, regression, association rules mining or genetic algorithms. It is important to note that in some cases hybrid RSs are not built by combining different recommendation techniques. In those cases they

represent combinations of different data sources, item or user representations, etc. embedded in a single RS. For this reason the number of the reported combinations is smaller than the number of total primary studies we analyzed.

4.4. Hybridization classes

Regarding the hybrid classes, weighted hybrid is the most popular. It often combines CF and CBF recommendations in a dynamic way (weights change over time). Feature combination is the second, putting together data from two or more sources. Cascade, switching, feature augmentation and meta-level have almost equal frequency of appearance whereas mixed hybrid is the least common class. There is also a last category we denoted as “Other” which includes 13.2% of the studies. It was not possible for us to identify a hybridization class of this recommenders based on Burke’s taxonomy (which might also need to be extended). In some studies hybrid RSs are not combinations of two or more recommendation strategies in a certain way. They put together different data sources and item or user representations in a single strategy. In this sense, the “Other” category means “we don’t know”.

Various mathematical constructs are used as “gluing” methods between the different components of the systems based on the hybridization class. Weighted, Mixed, Switching and Feature Combination are order-insensitive; there is no difference between a switching CF-CBF and a switching CBF-CF. In this sense these 4 classes are easier to concatenate compared to Cascade, Feature Augmentation and meta-level which are inherently ordered. The few mixed systems do not need the “glue” at all as their components generate recommendations independently from each other. Our results indicate that Weighted hybrids usually rely on weighted linear functions with static or dynamic weights which are updated based on the user feedback. Switching hybrids usually rely on distance/similarity measures such as Euclidean distance, Pearson correlation, Cosine similarity, etc. to decide which of the components to activate in a certain time. Feature combinations usually involve fuzzy logic to match the features obtained by one module with those of the other module. Feature augmentation, Cascade and Meta-level hybrids rely on even more complex and advanced mathematical frameworks such as probabilistic modeling, Bayesian networks, etc.

4.5. Application domains

A rich set of application domains was found as shown in Fig. 7. Many of the studies are domain independent (more than a quarter). They are not limited to any particular domain and the methods or algorithms they present can be applied in different domains with minor or no changes at all. Movies are obviously the most recommended items. It is somehow because of the large amount of public and freely accessible user feedback about movie preferences (i.e. many public movie datasets on the web¹⁰) which are highly helpful. There is also a rich set of algorithms and solutions (Netflix \$1M challenge was a big motivation to improve movie recommenders). This allows researchers to train and test their recommendation algorithms easily. Education or e-learning is another domain in which hybrid RSs are gaining popularity. The amount of educational material on the web has been increasing dramatically in the last years and MOOCs (Massive Open Online Course) are becoming very popular. Other somehow popular domains are music and web services. More detailed information about the application domains of recommender systems can be found at [33] where the authors illustrate each application domain category with real RS applications found in the web.

¹⁰<https://gist.github.com/entaroadun/1653794>.

4.6. Evaluation

Evaluation of Recommender Systems is an essential phase which helps in choosing the right algorithm in a certain context and for a certain problem. However, as explained in [34], evaluating recommender systems is not an easy task. Certain algorithms may perform better or worse in different datasets and it is not easy to decide what metrics to combine when performing comparative evaluations. With the three research questions about evaluation, we addressed different aspects of this delicate process. Based on our results most of the studies evaluate hybrid RSs by comparing them with similar methods. The experiments which are usually offline utilize accuracy or error metrics like MAE or RMSE and information retrieval metrics like precision, recall and F1. Similar results are reported in [35] where offline evaluations that typically measure accuracy are dominant. User surveys are less popular, using subjective quality assessments and occasionally precision or recall. These kind of experiments are mostly online (i.e. users interacting with the system and answering questions) and offer more direct and credible evaluation conclusions. From the results, we see that researchers find it easier to compare their system with other systems using public data rather than to perform massive user surveys for a more subjective and qualitative evaluation.

Regarding RS characteristics, accuracy results to be the most commonly evaluated characteristic of the hybrid RSs. This is partly because it is easy to represent and compute it by means of various measures that exist. The most frequent metrics used to evaluate accuracy are Precision, Recall and MAE. User satisfaction (subjective recommendation quality) comes second. It is evaluated by means of user surveys. There is a lot of discussion in the literature about recommendation diversity. In [36] the authors conclude that the user's overall liking of recommendations goes beyond accuracy and involves other factors like diversity. On the other hand, in [31] the authors agree that increasing diversity in recommendations comes with a cost in accuracy. Our results show that diversity is still less frequently evaluated. Actually most of the studies that try to provide diversity do it by conceding accuracy. In [23] the authors explore the use of serendipity and coverage as both characteristics and quality measures of RSs. They suggest that serendipity and coverage are designed to account for the quality and usefulness of the recommendations better than accuracy does. In our results serendipity is rarely evaluated.

It is important to note that the difference between recommendation characteristics and evaluation metrics is sometimes subtle. This is the case for coverage. Is coverage a recommendation characteristic, a recommendation metric or both? In some works like [23,34] coverage is considered as both a characteristic and metric. As a characteristic it reflects the usefulness of the system. The higher the coverage (more items predicted and recommended) the more useful the recommender system for the users. In other works like [37] it is only considered as a metric with which the authors evaluate diversity, another recommendation characteristic. In the studies we considered for this review coverage is both considered as a metric for estimating the diversity and as a recommendation characteristic of the systems. Few studies we analyzed evaluate the computational complexity of the systems they propose by measuring the execution time. Besides the new trends, the results indicate that accuracy is still the most frequently evaluated characteristic.

We also considered the public datasets used to perform the evaluation. With the exponential growth of the web content there are more and more public data and datasets which can be used to train and test new algorithms. These datasets usually come from highly visited web portals or services and represent user preferences about things like movies, music, news, books, etc. In [38] we present the characteristics of some of the most popular public datasets and the types of RSs they can be used for. It is convenient to exploit them for evaluating novel algorithms or recommendation techniques in offline experiments.

The evaluation process steps are clearly explained in [39]. The result of this review indicate that movie datasets led by MovieLens are very popular being used in more than 72% of the studies. This is somehow related with the fact that movie domain is also highly preferred. Many authors chose to experiment in the domain of movies to easily evaluate their prototypes. Music, web services, tourism, images datasets, etc. make up the rest of the datasets the studies use.

4.7. Future work

With RQ7 we tried to uncover the most important future work directions in hybrid recommender systems. Extending or improving the proposed solution is the most common future work the authors intend to undertake. Extension of the proposed solutions comes in diverse forms like (i) extend by applying more algorithms, (ii) extend the personalization level by adapting more to the user context and profile, (iii) extend by using more datasets or item features, etc. Performing a comprehensive evaluation is something in which many studies fail. This is why some authors present it as a future work. It usually happens in the cases when the authors implement their algorithm or method in a prototype. In these cases comparison with similar methods using accuracy metrics does not provide clear insights about recommendation or system quality. Reinforcing with subjective user feedback may be the best way to optimize evaluation of the system, making it more user oriented.

A highly desired characteristic from RSs is adapting to the user interest shifting or evolving over time, especially as a result of rapid context changes. As a result, different authors suggest to add context to their systems or to analyze different criteria of items or users as ways to improve the recommendation quality. Context-Aware Recommender Systems (CARS) and Multi-Criteria Recommender Systems (MCRS) are relatively new approaches which are gaining popularity in the field of RSs [40]. They are promoted by the increased use of mobile devices which reveal user details (i.e. the location) that can be used as important contextual inputs. Combining context and multiple criteria with other hybrid recommendation techniques could be a good direction in which to experiment.

Considering other application domains in which hybrid RSs could be applied is also stated by some authors. Many of the works were domain independent and can be easily adapted to different recommendation domains. One step further could be to have hybrid RSs recommend items from different (changing) domains and implement the so called cross domain recommender systems. Having found the best movie for the weekend, the user may also want to find the corresponding soundtrack or the book in which the movie may be based on. Cross-domain RSs are an emerging research topic [41,42]. Different recommendation strategies like CF and CBF could be specialized in different domains of interest and then joined together in a weighted, switching, mixed or other hybrid cross-domain RS which would recommend different items to its users.

Combining more data from different sources or with various item features was a way to create hybrid RSs. Using more data is a common trend not only in recommender systems but in similar disciplines as well. However, having and using big volumes of data requires scaling in computations. One way to achieve this high scalability is by parallelizing the algorithms following *MapReduce* model which could be a future direction as suggested in [43]. Experimenting with other hybrid recommendation classes is also possible in many cases. The results indicate that some hybrid classes are rarely explored (i.e. mixed hybrid appears in 3 studies only). It could be a good idea to experiment building CF-CBF, CF-CBF, CF-KBF or other types of mixed hybrids and observe what characteristics these systems could provide. Other future work suggestions include increasing personalization and reducing the computational cost of the system.

5. Conclusions

In this review work we analyzed 76 primary studies from journals and conference proceedings which address hybrid RSs. We tried to identify the most acute problems they solve to provide better recommendations. We also analyzed the data mining and machine learning techniques they use, the recommendation strategies they combine, hybridization classes they belong to, application domains and dataset, evaluation process, and possible future work directions.

With regard to the research problems cold-start, data sparsity and accuracy are the most recurrent problems for which hybrid approaches are explored. The authors typically use association rules mining in combination with traditional recommendation strategies to find user-item relations and compensate the lack of ratings in cold-start situations. We also found that matrix factorization techniques help to compress the existing sparse ratings and attain acceptable accuracy. It was also typical to find studies in which collaborative filtering was combined with other techniques such as fuzzy logic attempting to alleviate cold-start or data sparsity and at the same time provide good recommendation accuracy.

We also presented a classification of the included studies based on the different DM/ML techniques they utilize to build the systems and their recommendation technique combinations. K-NN classifier which is commonly used to construct the neighborhood in collaborative RSs, was the most popular among the data mining technique. On the other hand, CF was the most commonly used recommendation strategy, frequently combined with each of the other strategies attempting to solve any kind of problem.

We identified and classified the different hybridization approaches relying in the taxonomy proposed by Burke and found that the weighted hybrid is the most recurrent, obviously because of the simplicity and dynamicity it offers. Other hybridization classes such as meta level or feature augmentation are rare as they need complicated mathematical constructs to aggregate the results of the different recommenders they combine.

Concerning evaluation, accuracy is still considered the most important characteristic. The authors predominantly use comparisons with similar methods and involve error or prediction metrics in the evaluation process. This evaluation methodology is “hermetic” and often not credible. User satisfaction is commonly evaluated with subjective data feedback from surveys which are user oriented, more credible and thus highly suggested. Additionally, computational complexity was found in few cases. We also investigated what public datasets are typically used to perform evaluation of the hybrid systems. Based on our findings movie datasets led by MovieLens are the most popular, facilitating the evaluation process. Moreover movie domain was the most preferred for prototyping, among the numerous that were identified.

More than three-quarters of our included studies were published in the last five years. This high and growing number of recent publications in the field lets us believe that hybrid RSs are a hot and interesting topic. Our findings indicate that future works could be focused in context awareness of recommendations and models with which to formalize and aggregate several contextual factors inside a hybrid recommender. Such RSs could be able to respond to quick shifts of user interest with high accuracy.

We also found that there are many combinations of recommendation techniques or hybridization classes which are not explored. Thus they represent a good basis for future experimentations in the field. Using more data was another possible work direction we found. In the epoch of big data, processing more or larger dataset (as even more become available) with hybrid parallel algorithms could be a good way to alleviate the problem of scalability and also provide better recommendation quality. Other future work direction could be using hybrid RSs to build cross domain recommenders or improve the computation complexity of the existing techniques.

Acknowledgments

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Appendix

Selected papers

Table 14
Selected papers

P	Authors	Year	Title	Source	Publication details
P1	Wang, J.; De Vries, P. A.; Reinders, J. T. M.;	2006	Unifying User-based and Item-based Collaborative Filtering Approaches by Similarity Fusion	ACM	29th Annual International ACM SIGIR Conference on Research & Development on Information Retrieval, Seattle 2006
P2	Gunawardana, A.; Meek, C.;	2008	Tied Boltzmann Machines for Cold Start Recommendations	ACM	2nd ACM Conference on Recommender Systems, Lousanne, Switzerland, 23rd-25th October 2008
P3	Gunawardana, A.; Meek, C.;	2009	A Unified Approach to Building Hybrid Recommender Systems	ACM	3rd ACM Conference on Recommender Systems, New York, October 23–25, 2009
P4	Park, S. T.; Chu, W.;	2009	Pairwise Preference Regression for Cold-start Recommendation	ACM	3rd ACM Conference on Recommender Systems, New York, October 23–25, 2009
P5	Ghazanfar, M. A.; Prugel-Bennett, A.;	2010	An Improved Switching Hybrid Recommender System Using Naive Bayes Classifier and Collaborative Filtering	ACM	Proceedings of the International MultiConference of Engineers and Computer Scientists 2010, Vol I, Hong Kong, March 17–19, 2010
P6	Zhuhadar, L.; Nasraoui, O.;	2010	An Improved Switching Hybrid Recommender System Using Naive Bayes Classifier and Collaborative Filtering	ACM	Proceedings of the International MultiConference of Engineers and Computer Scientists 2010, Vol I, Hong Kong, March 17–19, 2010
P7	Hwang, C. S.;	2010	Genetic Algorithms for Feature Weighting in Multi-criteria Recommender Systems	ACM	Journal of Convergence Information Technology, Vol. 5, N. 8, October 2010
P8	Liu, L.; Mehandjiev, N.; Xu, D. L.;	2011	Multi-Criteria Service Recommendation Based on User Criteria Preferences	ACM	5th ACM Conference on Recommender Systems, Chicago, Oct 23rd–27th 2011
P9	Bostandjiev, S.; O'Donovan, J.; Hillerer, T.;	2012	TasteWeights: A Visual Interactive Hybrid Recommender System	ACM	6th ACM Conference on Recommender Systems, Dublin, Sep. 9th–13th, 2012
P10	Stanescu, A.; Nagar, S.; Caragea, D.;	2013	A Hybrid Recommender System: User Profiling from Keywords and Ratings	ACM	A Hybrid Recommender System: User Profiling from Keywords and Ratings
P11	Hornung, T.; Ziegler, C. N.; Franz, S.;	2013	Evaluating Hybrid Music Recommender Systems	ACM	2013 IEEE/WIC/ACM International Conferences on Web Intelligence (WI) and Intelligent Agent Technology (IAT)

Table 14, continued

P	Authors	Year	Title	Source	Publication details
P12	Said, A.; Fields, B.; Jain, B. J.;	2013	User-Centric Evaluation of a K-Furthest Neighbor Collaborative Filtering Recommender Algorithm	ACM	The 16th ACM Conference on Computer Supported Cooperative Work and Social Computing, Texas, Feb. 2013
P13	Hu, L.; Cao, J.; Xu, G.; Cao, L.; Gu, Z.; Zhu, C.;	2013	Personalized Recommendation via Cross-Domain Triadic Factorization	Scopus	22nd ACM International WWW Conference, May 2013, Brasil
P14	Christensen, I.; Schiaffino, S.;	2014	A Hybrid Approach for Group Profiling in Recommender Systems	ACM	Journal of Universal Computer Science, vol. 20, no. 4, 2014
P15	Garden, M.; Dudek, G.;	2005	Semantic feedback for hybrid recommendations in Recommendz	IEEE	IEEE 2005 International Conference on e-Technology, e-Commerce and e-Service
P16	Bezerra, B. L. D.; Carvalho, F. T.; Filho, V. M.;	2006	C2 :: A Collaborative Recommendation System Based on Modal Symbolic User Profile	IEEE	Proceedings of the 2006 IEEE/WIC/ACM International Conference on Web Intelligence
P17	Ren, L.; He, L.; Gu, J.; Xia, W.; Wu, F.;	2008	A Hybrid Recommender Approach Based on Widrow-Hoff Learning	IEEE	IEEE 2008 Second International Conference on Future Generation Communication and Networking
P18	Godoy, D.; Amandi, A.;	2008	Hybrid Content and Tag-based Profiles for Recommendation in Collaborative Tagging Systems	IEEE	IEEE 2008 Latin American Web Conference
P19	Aimeur, E.; Brassard, G.; Fernandez, J. M.; Onana, F. S. M.; Rakowski, Z.;	2008	Experimental Demonstration of a Hybrid Privacy-Preserving Recommender System	IEEE	The Third International Conference on Availability, Reliability and Security, IEEE 2008
P20	Yoshii, K.; Goto, M.; Komatani, K.; Ogata, T.; Okuno, H. G.;	2008	An Efficient Hybrid Music Recommender System Using an Incrementally Trainable Probabilistic Generative Model	IEEE	IEEE TRANSACTIONS ON AUDIO, SPEECH, AND LANGUAGE PROCESSING, VOL. 16, NO. 2, FEBRUARY 2008
P21	Maneeroj, S.; Takasu, A.;	2009	Hybrid Recommender System Using Latent Features	IEEE	IEEE 2009 International Conference on Advanced Information Networking and Applications
P22	Meller, T.; Wang, E.; Lin, F.; Yang, C.;	2009	New Classification Algorithms for Developing Online Program Recommendation Systems	IEEE	IEEE 2009 International Conference on Mobile, Hybrid, and On-line Learning
P23	Shambour, Q.; Lu, J.;	2010	A Framework of Hybrid Recommendation System for Government-to-Business Personalized e-Services	IEEE	IEEE 2010 Seventh International Conference on Information Technology
P24	Deng, Y.; Wu, Z.; Tang, C.; Si, H.; Xiong, H.; Chen, Z.;	2010	A Hybrid Movie Recommender Based on Ontology and Neural Networks	IEEE	A Hybrid Movie Recommender Based on Ontology and Neural Networks
P25	Yang, S. Y.; Hsu, C. L.;	2010	A New Ontology-Supported and Hybrid Recommending Information System for Scholars	Scopus	13th International Conference on Network-Based Information Systems
P26	Basiri, J.; Shakery, A.; Moshiri, B.; Hayat, M.;	2010	Alleviating the Cold-Start Problem of Recommender Systems Using a New Hybrid Approach	IEEE	IEEE 2010 5th International Symposium on Telecommunications (IST'2010)
P27	Valdez, M. G.; Alanis, A.; Parra, B.;	2010	Fuzzy Inference for Learning Object Recommendation	IEEE	IEEE 2010 International Conference on Fuzzy Systems

Table 14, continued

P	Authors	Year	Title	Source	Publication details
P28	Choi, S. H.; Jeong, Y. S.; Jeong, M. K.;	2010	A Hybrid Recommendation Method with Reduced Data for Large-Scale Application	IEEE	IEEE Transactions on systems, man and cybernetics – Part C: Applications and Reviews, VOL. 40, NO. 5, September 2010
P29	Ghazanfar, M. A.; Prugel-Bennett, A.;	2010	Building Switching Hybrid Recommender System Using Machine Learning Classifiers and Collaborative Filtering	IEEE	IEEE IAENG International Journal of Computer Science, 37:3, IJCS_37_3_09
P30	Castro-Herrera, C.;	2010	A Hybrid Recommender System for Finding Relevant Users in Open Source Forums	Scopus	IEEE 3rd International Conference on Managing Requirements Knowledge, Sept. 2010
P31	Tath, I.; Biturk, A.;	2011	A Tag-based Hybrid Music Recommendation System Using Semantic Relations and Multi-domain Information	IEEE	11th IEEE International Conference on Data Mining Workshops, Dec. 2011
P32	Kohi, A.; Ebrahimi, S. J.; Jalali, M.;	2011	Improving the Accuracy and Efficiency of Tag Recommendation System by Applying Hybrid Methods	IEEE	IEEE 1st International eConference on Computer and Knowledge Engineering (ICCKE), October 13–14, 2011
P33	Kohi, A.; Ebrahimi, S. J.; Jalali, M.;	2011	Improving the Accuracy and Efficiency of Tag Recommendation System by Applying Hybrid Methods	IEEE	IEEE 1st International eConference on Computer and Knowledge Engineering (ICCKE), October 13–14, 2011
P34	Fenza, G.; Fischetti, E.; Furno, D.; Loia, V.;	2011	A hybrid context aware system for tourist guidance based on collaborative filtering	Scopus	2011 IEEE International Conference on Fuzzy Systems, June 27–30, 2011, Taipei, Taiwan
P35	Shambour, Q.; Lu, J.;	2011	A Hybrid Multi-Criteria Semantic-enhanced Collaborative Filtering Approach for Personalized Recommendations	IEEE	2011 IEEE/WIC/ACM International Conferences on Web Intelligence and Intelligent Agent Technology
P36	Li, X.; Murata, T.;	2012	Multidimensional Clustering Based Collaborative Filtering Approach for Diversified Recommendation	IEEE	The 7th International Conference on Computer Science & Education July 14–17, 2012. Melbourne, Australia
P37	Shahriary, S.; Aghabab, M. P.;	2013	Recommender systems on web service selection problems using a new hybrid approach	IEEE	IEEE 4th International Conference on Computer and Knowledge Engineering, 2014
P38	Yu, C. C.; Yamaguchi, T.; Takama, Y.;	2013	A Hybrid Recommender System based Non-common Items in Social Media	IEEE	IEEE International Joint Conference on Awareness Science and Technology and Ubi-Media Computing, 2013
P39	Buncle, J.; Anane, R.; Nakayama, M.;	2013	A Recommendation Cascade for e-learning	IEEE	2013 IEEE 27th International Conference on Advanced Information Networking and Applications
P40	Bedi, P.; Vashisth, P.; Khurana, P.;	2013	Modeling User Preferences in a Hybrid Recommender System using Type-2 Fuzzy Sets	Scopus	IEEE International Conference on Fuzzy Systems, July 2013
P41	Andrade, M. T.; Almeida, F.;	2013	Novel Hybrid Approach to Content Recommendation based on Predicted Profiles	IEEE	2013 IEEE 10th International Conference on Ubiquitous Intelligence & Computing

Table 14, continued

P	Authors	Year	Title	Source	Publication details
P42	Yao, L.; Sheng, Q. Z.; Segev, A.; Yu, J.;	2013	Recommending Web Services via Combining Collaborative Filtering with Content-based Features	IEEE	2013 IEEE 20th International Conference on Web Services
P43	Luo, Y.; Xu, B.; Cai, H.; Bu, F.;	2014	A Hybrid User Profile Model for Personalized Recommender System with Linked Open Data	IEEE	IEEE 2014 Second International Conference on Enterprise Systems
P44	Sharif, M. A.; Raghavan, V. V.;	2014	A Clustering Based Scalable Hybrid Approach for Web Page	IEEE	2014 IEEE International Conference on Big Data
P45	Xu, S.; Watada, J.;	2014	A Method for Hybrid Personalized Recommender based on Clustering of Fuzzy User Profiles	IEEE	IEEE International Conference on Fuzzy Systems (FUZZ-IEEE) July 6–11, 2014, Beijing, China
P46	Lee, K.; Lee, K.;	2014	Using Dynamically Promoted Experts for Music Recommendation	IEEE	IEEE Transactions on Multimedia, VOL. 16, NO. 5, August 2014
P47	Chughtai, M. W.; Selamat, A.; Ghani, I.; Jung, J. J.;	2014	E-Learning Recommender Systems Based on Goal-Based Hybrid Filtering	IEEE	International Journal of Distributed Sensor Networks Volume 2014pages
P48	Li, Y.; Lu, L.; Xufeng, L.	2005	A hybrid collaborative filtering method for multiple-interests and multiple-content recommendation in E-Commerce	Science Direct	Expert Systems with Applications 28 (2005) 6777
P49	Kunaver, M.; Pozrl, T.; Pogacnik, M.; Tasic, J.;	2007	Optimisation of combined collaborative recommender systems	Science Direct	International Journal of Electronics and Communications (AEU), 2007, 433–443
P50	Albadvi, A.; Shahbazi, M.;	2009	A hybrid recommendation technique based on product category attributes	Scopus	Expert Systems with Applications 36 (2009) 1148011488
P51	Capos, L. M.; Fernandez-Luna, J. M.; Huete, J. F.; Rueda-Morales, M. A.;	2010	Combining content-based and collaborative recommendations: A hybrid approach based on Bayesian networks	Science Direct	International Journal of Approximate Reasoning 51 (2010) 785799
P52	Barragans-Martnez, A. B.; Costa-Montenegro, E.; Burguillo, J. C.; Rey-Lopez, M.; Mikic-Fonte, F. A.; Peleteiro, A.;	2010	A hybrid content-based and item-based collaborative filtering approach to recommend TV programs enhanced with singular value decomposition	Science Direct	International Journal of Information Sciences 180 (2010) 42904311
P53	Wen, H.; Fang, L.; Guan, L.;	2012	A hybrid approach for personalized recommendation of news on the Web	Science Direct	International Journal of Expert Systems with Applications 39 (2012) 58065814
P54	Porcel, C.; Tejeda-Lorente, A.; Martinez, M. A.; Herrera-Viedma, E.;	2012	A hybrid recommender system for the selective dissemination of research resources in a Technology Transfer Office	Science Direct	International Journal of Information Sciences 184 (2012) 119
P55	Noguera, J. M.; Barranco, M. J.; Segura, R. J.; Martinez, L.;	2012	A mobile 3D-GIS hybrid recommender system for tourism	Science Direct	International Journal of Information Sciences 215 (2012) 3752

Table 14, continued

P	Authors	Year	Title	Source	Publication details
P56	Salehi, M.; Pourzaferani, M.; Razavi, S. A.;	2013	Hybrid attribute-based recommender system for learning material using genetic algorithm and a multidimensional information model	Science Direct	Egyptian Informatics Journal (2013) 14, 6778
P57	Zang, Z.; Lin, H.; Liu, K.; Wu, D.; Zhang, G.; Lu, J.;	2013	A hybrid fuzzy-based personalized recommender system for telecom products/services	Science Direct	International Journal of Information Sciences 235 (2013) 117129
P58	Kardan, A. A.; Ebrahimi, M.;	2013	A novel approach to hybrid recommendation systems based on association rules mining for content recommendation in asynchronous discussion groups	Science Direct	International Journal of Information Sciences 219 (2013) 93110
P59	Lucas, J. P.; Luz, N.; Moreno, M. N.; Anacleto, R.; Figueiredo, A. A.; Martins, C.;	2013	A hybrid recommendation approach for a tourism system	Science Direct	International Journal of Expert Systems with Applications 40 (2013) 35323550
P60	Son, L. H.;	2014	HU-FCF: A hybrid user-based fuzzy collaborative filtering method in Recommender Systems	Science Direct	International Journal of Expert Systems with Applications 41 (2014) 68616870
P61	Son, L. H.;	2014	HU-FCF++: A novel hybrid method for the new user cold-start problem in recommender systems	Scopus	Engineering Applications of Artificial Intelligence 41(2015)207222
P62	Lekakos, G.; Caravelas, P.;	2006	A hybrid approach for movie recommendation	Springer	Multimed Tools Appl (2008) 36:5570 DOI 10.1007/s11042-006-0082-7, Springer
P63	Lekakos, G.; Giaglis, G. M.;	2007	A hybrid approach for improving predictive accuracy of collaborative filtering algorithms	Springer	User Model User-Adap Inter (2007) 17:540 DOI 10.1007/s11257-006-9019-0, Springer
P64	Degemmis, M.; Lops, P.; Semeraro, G.;	2007	A content-collaborative recommender that exploits WordNet-based user profiles for neighborhood formation	Springer	User Model User-Adap Inter (2007) 17:217255, DOI 10.1007/s11257-006-9023-4, Springer
P65	Cho, J.; Kang, E.;	2010	Personalized Curriculum Recommender System Based on Hybrid Filtering	Springer	ICWL 2010, LNCS 6483, pp. 6271, 2010, Springer
P66	Aksel, F.; Biturk, A.;	2010	Enhancing Accuracy of Hybrid Recommender Systems through Adapting the Domain Trends	Scopus	Workshop on the Practical Use of Recommender Systems, Algorithms and Technologies held in conjunction with RecSys 2010. Sept. 30, 2010, Barcelona
P67	Lampropoulos, A. S.; Lampropoulos, P. S.; Tsihrintzis, G. A.;	2011	A Cascade-Hybrid Music Recommender System for mobile services based on musical genre classification and personality diagnosis	Springer	Multimed Tools Appl (2012) 59:241258 DOI 10.1007/s11042-011-0742-0, Springer
68	Chen, W.; Niu, Z.; Zhao, X.; Li, Y.;	2012	A hybrid recommendation algorithm adapted in e-learning environments	Springer	World Wide Web (2014) 17:271284 DOI 10.1007/s11280-012-0187-z

Table 14, continued

P	Authors	Year	Title	Source	Publication details
P69	Sanchez, F.; Barrile, M.; Uribe, S.; Alvarez, F.; Tena, A.; Mendez, J. M.;	2012	Social and Content Hybrid Image Recommender System for Mobile Social Networks	Springer	Mobile Netw Appl (2012) 17:782795 DOI 10.1007/s11036-012-0399-6, Springer
P70	Zheng, X.; Ding, W.; Xu, J.; Chen, D.;	2013	Personalized recommendation based on review topics	Scopus	SOCA (2014) 8:1531 DOI 10.1007/s11761-013-0140-8
P71	Cao, J.; Wu, Z.; Wang, Y.; Zhuang, Y.;	2013	Hybrid Collaborative Filtering algorithm for bidirectionalWeb service recommendation	Springer	Knowl Inf Syst (2013) 36:607627 DOI 10.1007/s10115-012-0562-1
P72	Burke, R.; Vahedian, F.; Mobasher, B.;	2014	Hybrid Recommendation in Heterogeneous Networks	Springer	UMAP 2014, LNCS 8538, pp. 4960, 2014, Springer
P73	Nikulin, V.;	2014	Hybrid Recommender System for Prediction of the Yelp Users Preferences	Springer	ICDM 2014, LNAI 8557, pp. 8599, 2014, Springer
P74	Sarne, G. M. L.;	2014	A novel hybrid approach improving effectiveness of recommender systems	Springer	J Intell Inf Syst DOI 10.1007/s10844-014-0338-z
P75	Zhao, X.; Niu, Z.; Chen, W.; Shi, C.; Niu, K.; Liu, D.;	2014	A hybrid approach of topic model and matrix factorization based on two-step recommendation framework	Springer	J Intell Inf Syst DOI 10.1007/s10844-014-0334-3, Springer
P76	Nilashi, M.; Ibrahim, O. B.; Ithnin, N.; Zakaria, R.;	2014	A multi-criteria recommendation system using dimensionality reduction and Neuro-Fuzzy techniques	Springer	Soft Comput DOI 10.1007/s00500-014-1475-6, Springer-Verlag Berlin Heidelberg 2014



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Literature Review on Metacognition and its Measurement

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Abstract

Metacognition is a structure that is referred as fuzzy by many scholars and has very diverse meanings. Much research has been conducted for more than 30 years in order to access the inner side of this structure, which is really hard to grasp. In this paper, the review of literature aims to reveal the theoretical and educational structure of the concept of metacognition chiefly on the basis of the relevant research. Then, an attempt will be made to determine the difference between cognition and metacognition. Finally, difficulties that are encountered in the measurement of metacognition and the methods and tools that will be used in the measurement of metacognition will be determined.

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Keywords: Cognition, metacognition, measurement of metacognition;

1. Introduction

Metacognition is a structure that is referred as fuzzy by many scholars and has very diverse meanings. Much research has been conducted for more than 30 years in order to access the inner side of this structure, which is really hard to grasp. The roots of present metacognition studies are based on cognitive psychology (Hart, 1965; Peters 2007), on cognitive development psychology (Piaget, 1950; Steinbach 2008), and on social development psychology (Tsai 2001; Vygotsky, 1962). Hart (1965) was concerned with the correctness of the judgments that adults made about memory which reveals valid predictors of behaviour (Peters, 2007). Piaget (1950), on the other hand, was the one who first mentioned “knowing the knowing and thinking the thinking” in the early years of cognitive development and personal information epistemology (Steinbach, 2008). Vygotsky (1962) maintained that consciousness and conscious control were basic contributors during school years (Tsai, 2001).

According to Georghiades (2004), being aware of one's cognition was already been mentioned by Plato. Likewise, Aristotle pointed out that mind used a different power above and beyond seeing and hearing and thus laid the foundations for thinking about metacognition long before (Sandí-Ureña, 2008). However, John Flavell (1976) is known to be the first scholar who used the concept of metacognition, a term he derived from the term metamemory and he used in his initial works in the early 1970s.

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2. Metacognition

Various words that are synonymous with metacognition have been in use in recent years. According to reports cited by Steinbach (2008), while some researchers use the word self-management for metacognition (O'Neil & Speilberger, 1979), others prefer the words metamentation (Bogdan, 2000) or meta-learning (Cross & Steanmand, 1996). Likewise, Veenman, Van Hout-Wolters and Afflerbach (2006) state some different terms used in the relevant literature in connection with metacognition such as metacognitive beliefs, executive skills, metacomponents and judgments of learning.

Today, metacognition is used as an umbrella term encompassing the structures that are related to individuals' thinking processes and information (Leader, 2008). Although various definitions are encountered in the relevant literature, probably the most common definition of metacognition is that metacognition is individuals' having information about their cognitive structure and being able to organize this structure (Flavell, 1979; Wellman, 1985; Brown, 1987; Jacobs and Paris, 1987; Schraw, 1994; Livingston, 1997; Dunlosky and Hertzog, 2000; Georghiades, 2004).

John Flavell (1976), who led studies regarding the concept of metacognition through his research, defining metacognition as follows: "metacognition refers to one's knowledge concerning one's own cognitive processes and products or anything related to them" (p.232). Flavell (1979) was concerned with investigating whether children were aware of understanding some components that govern their memories and cognitions. This research provided significant evidence about the fact that children possessed the ability to reflect their own cognitive processes. After this research, Flavell defined metacognition as information and cognition about the cognitive phenomenon and conceptualized it as the learner's information about his or her own cognition.

Brown (1978) conducted many studies after Flavell and focused on understanding information or the problems related to either effective use of information or understanding information for which a clear definition has been provided. He defined metacognition as students' awareness and organization of thinking processes that they use in planned learning and problem solving situations. Wellman (1985) defines metacognition as "thinking about thinking or a person's cognition about cognition" (p.1). Metacognition occurs as a result of one's individual evaluation and observation of their cognitive behavior in a learning environment (Ayersman, 1995). According to Baker and Brown (1980), metacognition is a theoretical structure where learners take effective responsibility of their learning and is individuals' being aware of their learning and its management.

Metacognition can be explained as individuals' information while they are learning or fulfilling a task and a deliberate organization in cognitive processes (Brown, Bransford, Ferrara & Campione, 1983; Miller, 1985). Swanson (1990) defines metacognition as individuals' awareness of their ability to monitor, regulate and control their own activities concerning learning. Metacognition generally means higher level thinking about how a learning task will be handled, and making plans on processes of observing and evaluating comprehension (Livingston, 1997). Wilson (1998) regards metacognition as knowledge and awareness of thinking processes and strategies (together with the ability to evaluate and organize these processes). Scarr and Zanden (1984), on the other hand, define metacognition as individuals' awareness and comprehension of processes of regulating their mental state, skills, memory and behavior.

Although there are many different definitions concerning metacognition, the one common point is to monitor strategies for the learning process (Bonner, 1988) and many other researchers blend two different approaches that emphasize the importance of cognitive states and processes and the control of the executable aspect of metacognition in a single definition (Paris & Winograd, 1990). This definition involves individuals' planning of their information about their own and others' cognitive processes before they fulfill their task, observing their thinking, learning and understanding while performing a task, controlling and regulating their thinking by making arrangements on site and evaluating after they have completed their task (Scott, 2008).

3. Difference between Cognition and Metacognition

It will be useful to reveal the difference between cognition and metacognition while explaining the concept of metacognition. The concepts of cognition and metacognition are different although they are related to each other. While metacognition is necessary to understand how a task will be performed, cognition is required to fulfill a task (Schraw, 2001). While cognition means being aware of and understanding something, metacognition is being aware of and knowing how one learns in addition to learning and understanding something (Senemoğlu, 2005). According to Gourgey (1998), on the other hand, cognition is necessary to form the learning process and information while metacognition is required for individuals to observe, develop, and evaluate their own processes and apply their knowledge to new situations. Therefore, metacognition is a basic requirement for cognitive effectiveness.

It is necessary to understand the relationship between metacognition and cognition. Metacognitive activities occur before cognitive activities (planning), during activities (monitoring) or after activities (evaluating). We can give as an example a student who uses self-observation strategy during reading to exemplify the relationship between metacognition and cognition. The student knows that s/he can not comprehend (metacognition) what s/he is reading. At the same time, s/he knows that s/he can understand the text better when s/he prepares a conceptual map or makes a summary (cognition). This relationship is shown in Figure 1. (Wahl, 2007; cited by Altındağ, 2008).

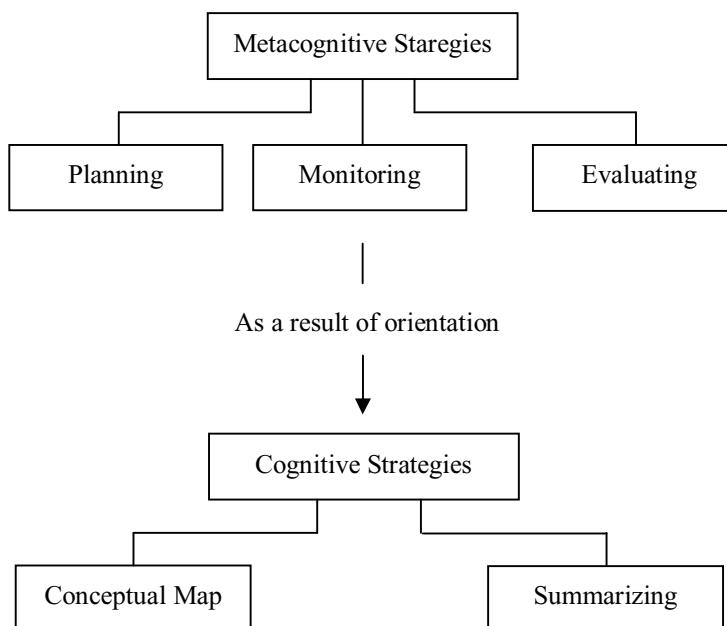


Figure 1. Relationship between cognition and metacognition

4. Measurement of Metacognition

As stated by Peters (2007), existence of metacognition was first investigated by Hart (1965), Underwood (1966) and Arbuckle and Cuddy (1969) in the 1960s. In his study, Hart (1965) asked participants questions that involved general information. Then, he asked them what they thought about the solution to the problem for each question. He concluded that the participants' ideas about the solution to the problem were definite predictors of the correct answers to the questions. Underwood (1966), on the other hand, asked the participants about their views concerning the difficulty of each item on the test and demonstrated that the ideas of each individual could predict their own

learning. Arbuckle and Cuddy (1969) worked on individual judgments about learning and concluded that individuals' judgments on their own learning were highly accurate.

Measurement of metacognition is naturally difficult because metacognition is not an explicit behavior. Metacognition is not internal process only; on the contrary, individuals are not aware of these processes. As cited by Sandí-Ureña (2008) from Veenman (2005), he defined methods of measuring metacognition, via the temporary relationships of the method of measurement concerning the implementation of a task, as probable if it was implemented before the task, simultaneous if it was implemented during the task and retrospective if it was implemented after the task. Measurement tools that are used to measure metacognition can be investigated in two categories, namely reports based on an individual's own telling (questionnaires and interviews) and objective behavior measurements (i.e. systemic observation and think aloud protocols). The method of measuring metacognition, on the other hand, can be determined according to the type of the measurement tool that was used to measure metacognition.

Simultaneous (synchronic) measurement of metacognition is implemented using tools that cause considerable loss of time and require that participants be evaluated individually. Tools that are most frequently used in the simultaneous measurement of metacognition are "think aloud protocols and systematic observations" (D. Rickey, 1999; Veenman, 2005; cited by Sandí-Ureña, 2008). Think aloud protocols allow the researcher to determine students' metacognitive ideas "online". Thus, students tell you verbally how they handle a certain problem. There are two problems in this type of measurement. One of those is that think aloud protocols may prevent students from learning the present materials while they express their metacognitive opinions verbally. The second is that while think aloud protocols are useful in the laboratory conditions, they are not functional in the classroom environment because when students are asked to think aloud while they are performing a task, it is necessary that they leave their typical learning environment. If the point of interest is how students learn in a classroom environment and how they use metacognitive thinking, think aloud protocols are not appropriate (Scott, 2008). Although systematic observations are useful in determining students' non-verbal metacognitive behavior diachronically, it also involves some disadvantages such as implementation with a small number of students and difficulty of student control. The tools that are most commonly used in probable and retrospective evaluation of metacognition are questionnaires and interviews.

The questionnaire is one of the most frequently used tools for measuring metacognition. However, it has both positive and negative aspects. The basic drawbacks of a questionnaire based on an individual's own report are the possibility that the students may be reluctant to express their ideas and experiences, the possibility that the questionnaires may not have been understood fully by all of the students, and the possibility that the questions might stimulate socially attractive questions (Baker & Cerro, 2000; cited by Scott, 2008). However, the positive aspects of questionnaires outweigh their negative aspects in terms of certain research questions. First, questionnaires enable researchers to evaluate larger student groups in one go without interfering with their classroom experiences. Questionnaires can be easily administered to groups and evaluated quickly and objectively (Tobias & Everson, 1996). Second, in contrast to interviews, questionnaires attain equality for all students in the collection of data that vary from student to student depending on the students' initial reactions. Finally, questionnaires can be used reliably and effectively in some structures where it is not possible to observe motivation and cognitive engagement (Pintrich & DeGroot, 1990).

Interviews are useful in that they enable an in-depth investigation of students' ideas. Interviews have the power to demand the students to expand on the answers that they have given if they have responded to the interview questions in the form of "yes" and "no". The basic problem concerned with using interviews in measuring metacognition is that it causes loss of time due to the fact that the method requires a mutual and interactive communication process based on asking and answering questions and that it can not be implemented in a classroom environment (Scott, 2008).

5. Conclusion

To sum up, it can be said that teaching students how to use metacognitive strategies increases academic achievement (Biggs, 1988). Students with advanced metacognitive skills are those who are aware of what they have learned and what they do not know. Generally, students with advanced metacognitive skills may monitor their own learning, express their opinions about the information, update their knowledge and develop and implement new learning strategies to learn more. In comparison to other students, students using their metacognitive skills effectively are those who are more aware of their strengths and weaknesses and strive to improve their learning skills further (Bransford, Brown & Cocking, 1999). According to Jones, Farquhar and Surry (1995), the further students' awareness of metacognition is improved, the more students' effectiveness is increased.

Despite to efforts aimed at increasing awareness, teaching and use of metacognition, studies concerning evaluation of metacognition are not parallel to the interest shown in metacognition. A lack of appropriate evaluation has been stated as an obstacle to the improvement of researches. Currently, the need for tools to measure metacognition continues. Schraw (2009) points out the difficulty of measuring metacognition and states that a single method that enables simultaneous connection to metacognition processes and allows for measurement of all of these processes alone does not exist. Tobias and Everson (2002) emphasize this point and state that metacognition is measured on the basis of observations, dialogues and individuals' self-reports. In conclusion, there is no single tool that can measure metacognition alone.

Note

The present study has been compiled from the first author's doctoral dissertation entitled "Effects of Metacognitive Instructional Strategies in Computer Course", which was completed in Program of Curriculum and Instruction, Department of Educational Sciences at Graduate School of Educational Sciences, Selcuk University.

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THE IMPACT OF METACOGNITION ON ENTREPRENEURIAL ORIENTATION: RESEARCH-IN-PROGRESS

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ABSTRACT

The purpose of this study is to investigate how individuals' metacognitions impact their entrepreneurial orientations and performances. Based on the two metacognition dimensions (metacognitive awareness, metacognitive skill), the three entrepreneurial orientation dimensions (innovativeness, risk taking, and proactiveness) and the three entrepreneurial tasks (growth in sales, return on sales, customer satisfaction), this study develops the research model and the eight hypotheses to explore the relationship among metacognition, EO and entrepreneurial task. This study will have several meaningful contributions to entrepreneurial research field as well as to strategic research field. First, regarding entrepreneurial metacognition, only a few empirical studies have been conducted thus far. Second, there are also rare empirical research works which examine the relationship between entrepreneurial metacognitions and their orientations. Even more, there is no existent empirical research work that investigates how entrepreneurial metacognition impacts the entrepreneurial performances. Therefore, this research can help entrepreneurs as well as entrepreneurial firms, more systematically to understand how their metacognitive aspects influence their entrepreneurial tasks.

Keywords: Metacognitions, Entrepreneurial Orientations, Entrepreneurial Tasks

INTRODUCTION

This study aims at exploring how individuals' metacognitions influence their entrepreneurial orientations and performances. In particular, this study intends to examine the following research questions:

- (1) Are the metacognitions of individuals related to the entrepreneurial orientations?
- (2) How do the metacognitive knowledge and skills influence the entrepreneurial orientations?
- (3) How do the metacognitive knowledge and skills impact the entrepreneurial tasks?

THEORETICAL BACKGROUNDS

Metacognition. Michael & Dean (2010) assert that foundations of an entrepreneurial mindset are metacognitive in nature, and entrepreneurs formulate and inform "higher-order" cognitive strategies in the pursuit of entrepreneurial purposes. In general, metacognition can be described as the awareness and understanding of one's own cognitive processes. Specifically, metacognition can be defined by the following five dimensions: metacognitive knowledge, metacognitive experience, metacognitive control, goal orientation, and monitoring (Flavell, 1979, 1987; Griffin & Ross, 1991; Nelson, 1996; Michael & Dean, 2009).

Entrepreneurial Orientation. EO is significantly important not only for the survival and growth of firms but also for the economic prosperity of nations (Morris, 1998). Lumpkin & Dess (1996) define entrepreneurial orientations (EO) as the practices processes, and decision-making activities that lead to new entry. In other words, EO is different from entrepreneurship itself. Although entrepreneurship simply refers to new entry, a firm's EO refers to the entrepreneurial process, namely how entrepreneurship is undertaken—the methods, practices, and decision-making styles used to act entrepreneurially (Sang & Suzanne, 2000). Miller (1983) adopted three dimensions of EO, "innovativeness," "risk taking," and "proactiveness" in order to characterize entrepreneurship. Later, Lumpkin & Dess (1996) suggested two more dimensions of EO, "autonomy," and "competitive aggressiveness."

RESEARCH MODEL AND HYPOTHESES

According to the similarity, this study classifies five metacognition dimensions into two categories: metacognitive awareness (metacognitive knowledge and metacognitive experience) and metacognitive skills (metacognitive control, goal orientation, and monitoring). Also, this study embraces the Miller's three EO dimensions (innovativeness, risk taking, and proactiveness) and builds up the following hypotheses to investigate the relationship among metacognition, EO and entrepreneurial task:

Hypothesis 1a. The metacognitive awareness is positively related to the entrepreneurial innovativeness orientation.

Hypothesis 1b. The metacognitive awareness is positively related to the entrepreneurial risk taking orientation.

Hypothesis 1c. The metacognitive awareness is positively related to the entrepreneurial proactiveness orientation.

Hypothesis 2a. The metacognitive skill positively influences to the entrepreneurial innovativeness orientation.

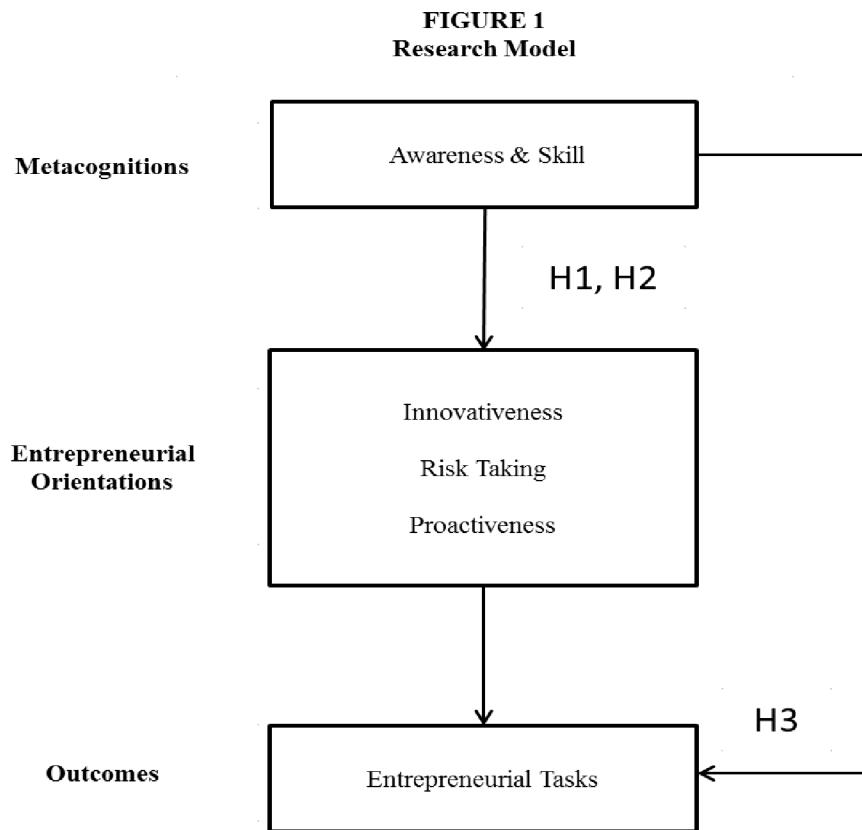
Hypothesis 2b. The metacognitive skill positively influences to the entrepreneurial risk taking orientation.

Hypothesis 2c. The metacognitive skill positively influences to the entrepreneurial proactiveness orientation.

Hypothesis 3a. The metacognitive awareness positively impacts the entrepreneurial tasks.

Hypothesis 3b. The metacognitive skill positively impacts the entrepreneurial tasks.

Figure 1 illustrates the conceptual framework of this research.



METHODOLOGY

A questionnaire is used as a survey in this study and comprises of the two metacognition dimensions (metacognitive awareness, metacognitive skill), the three EO dimensions (innovativeness, risk taking, and proactiveness), and the three entrepreneurial tasks (growth in sales, return on sales, customer satisfaction). The survey participants will be asked to rate their perceptions on these complex questions.

There are several criteria in choosing target respondents. The first criterion is choosing a single respondent from same company. The second criterion is the position of the target respondent in the organization; it is preferred that respondents are actual entrepreneurs of firms. The third criterion is that the target respondent is likely to have knowledge of firm's primary strategic implementation as well as knowledge of firm's performance. If there is more than one subject from the same organization, the target respondent is chosen on the basis of position in the organization (the highest rank among the target respondents) and the likelihood of his/her access to the information requested in the questionnaire.

In terms of data analysis, in order to look over the demographics of the respondent organizations, the frequency distributions of the number of employees, industries represented and

the types of firms will be generated. The assumptions of multivariate analysis will be tested. Moreover, reliability and validity tests will be conducted. The research model will be tested by a linear structural relations analysis (LISREL) (Kerlinger, 1986; Bobko, 1991; Joreskog & Sorbom, 1993).

CONCLUSION

I expect this research will have several meaningful contributions to entrepreneurial research field as well as to strategic research field. First, regarding entrepreneurial metacognition, only a few empirical studies have been conducted so far. Second, there are also rare empirical research works which examine the relationship between entrepreneurial metacognitions and their orientations. Even more, there is no existent empirical research work that investigates how entrepreneurial metacognition impacts the entrepreneurial performances. Therefore, this research can help entrepreneurs as well as entrepreneurial firms, more systematically to understand how their metacognitive aspects influence their entrepreneurial tasks.

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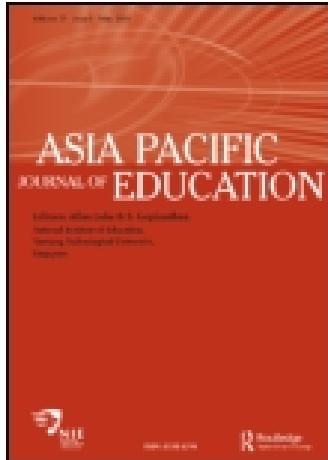
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Metacognition in Mathematical Problem Solving

Philip Wong

Abstract

Metacognition is considered by most educationists as an element necessary for many cognitive tasks. In problem solving, it has been said that possessing knowledge alone is insufficient and problem solvers need to exhibit high level cognitive skills like "self-regulation skills" (also known as metacognitive strategies) for successful problem solving.

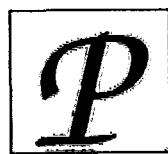
A study on students' metacognitive strategies was carried out with over a thousand secondary and pre-university students from 12 schools. A questionnaire adapted from Biggs (1987) was administered to students at various levels (Secondary 2, Secondary 4, Pre-University 1), from different academic tracks (General, Science, Arts) and academic streams (Special, Express, and Normal). They were required to self-report on their metacognitive beliefs; their use of metacognitive strategies in mental tasks involving memory, problem solving and comprehension; and their attitudes towards the learning of various academic subjects. 20 items from the questionnaire which were related to problem solving were categorized into four stages, namely, orientation, organisation, execution and verification and data from these items were analysed.

Some findings that emerged were:

- (a) Normal stream students exhibited a lower usage of metacognitive strategies as compared to students from the Express and Special streams.
- (b) Metacognitive strategies used by Normal stream students tended to be of the "surface" type.
- (c) There was no significant difference in the frequency of usage of metacognitive strategies between students from different academic tracks.
- (d) During the problem solving process, students spent most time on evaluation of answers rather than on monitoring their understanding.
- (e) Students from different levels (Secondary 2, Secondary 4 and Pre-University) exhibited similar frequency of usage of metacognitive strategies in problem solving.

The implications of these findings on future research and development projects as well as the teaching of metacognitive strategies are discussed in the paper.

Descriptors: Metacognition, Mathematics, problem solving, learning strategies



roblem solving is a complex task involving many types of knowledge and skills. Skills in planning, monitoring and revising strategies are as important as having a large

body of knowledge. It is undeniable that problem solving requires specialized knowledge such as linguistic, factual, schematic, strategic and procedural knowledge (Mayer, 1987). A number of researchers have also included metacognitive knowledge as another important factor that differentiates between the good and the average problem solver (Gagne, 1985; Lester 1982).

Previous studies on metacognition have concentrated on tasks involving reading and memory work and little work has been done with metacognition in problem solving. In mathematics, there is much interest to make students aware of metacognition and to develop their metacognitive skills. Lately researchers have begun to look at metacognitive skills in problem solving and have started to develop theoretical frameworks (Garofalo & Lester, 1985; Lester, 1985, Schoenfeld, 1985).

Metacognition is generally considered as "knowing about knowing" or what Schmitt and Newby (1986) refer to as "a body of knowledge that reflects knowledge itself". In other words, metacognition involves knowing the cognitive processes associated with an instructional task, and being able to use and monitor appropriate cognitive processes during the task. Although metacognition has been loosely defined, most psychologists (eg Brown, 1978; Flavell, 1976) consider metacognition to consist of two separate but related aspects of knowledge about cognition and regulation of cognition.

Knowledge about cognition implies that a person is knowledgeable about variables that will affect one's instructional performance in a learning situation or during an instructional process. Identifying one's weaknesses or strengths in certain topics of mathematics, realizing that one is careless in computation and tends to make computational mistakes, recognizing that one is weak in processing spatial and visual information, and to be aware of the different effects of semantic and syntactic structures (eg, vocabulary, extraneous information and order of events) on the difficulty of word problems are some examples of knowledge of cognition.

Regulation of cognition involves the type of decision behaviours exhibited in order to plan, monitor and evaluate one's action. Sternberg (1983) labels these types of behaviours as executive skills and has even proposed certain training strategies for the development of these executive skills. Although these skills are trainable, it is also believed that the regulation process is controlled by one's cognitive

knowledge (Kluwe, 1987). In mathematics problem solving, for example, a student who believes that he/she tends to make computation mistakes and thus slows down and proceeds cautiously during the computation part of problem solving and re-checking the answers, is said to be exhibiting this executive skill.

This self-regulation process is important for successful problem solving. Schoenfeld (1985) after an analysis of college students' protocol of their problem solving processes, concluded that at the self-control level, the lack of monitoring and assessing the situation could lead to failure in problem solving. Despite its importance, this cognitive procedure is not clearly demonstrated by young children and college students. Garofalo and Lester (1985) in their research found that young children did not routinely analyse information provided in the problem and did not monitor progress or validate the results. College students too, were not very efficient in regulating their problem solving behaviours. Schoenfeld (1985) found that the overall quality of college students' monitoring, assessing and executive decision-making in problem solving was relatively poor.

Metacognition in Problem Solving

Using Polya's (1957) heuristic problem-solving model as a foundation, Lester and associates (Lester, 1985; Garofalo & Lester, 1985) proposed a cognitive-metacognitive framework for performance in various mathematical tasks. The framework consists of four cognitive components of orientation, organization, execution and verification. The four components correspond to Polya's four phases of problem solving of understanding, planning, carrying out the plan, and looking back. However, Lester differentiates his framework from Polya's as he believes that his "model purports to describe the categories of the cognitive component in terms of points during problem solving where metacognitive actions might occur" (Lester, 1985; p 62). The four components can be briefly described as follows:

- (1) **ORIENTATION:** At this stage, students need to assess and understand the problem. The skills exercised at this stage would be those of comprehension; analysis of information; assessment of familiarity of problem and task difficulty and the formation of internal representation.
- (2) **ORGANIZATION:** This involves identifying goals, then planning for the whole task and sub-tasks in order to achieve the goals and sub-goals.
- (3) **EXECUTION:** The monitoring of behaviours exhibited in the execution of the plans falls into this category. It includes monitoring computation actions, maintaining progress towards the goal and assessing trade-off decisions between factors influencing the success of the problem-solving process.
- (4) **VERIFICATION:** This stage involves the monitoring and evaluation of the three components of orientation, organization and the execution of the whole problem-solving process.

Each component is controlled by metacognitive decisions made by the individual and the type of decisions will depend on his/her own knowledge of metacognition. For example, in the cognitive component of orientation, an individual may want to rephrase the text in order to help him/her understand the problem situation better or if the individual believes that he/she is better at processing visual information, he/she may reorganize and represent the text information visually. Thus, an individual with better metacognitive knowledge can use his/her executive decisions for better planning, execution, and monitoring of the problem solving process and, hopefully, achieve higher success in solving problems. The depth of one's metacognitive knowledge can influence the type of strategies one uses for monitoring and regulating cognition during problem solving. In the orientation component, for example, an individual may use different types of strategies: "surface" strategy such as re-reading the

problem, or "deep" strategy such as recalling old materials to link new materials found in the problem or "achieving" strategy such as analysing and representing problem information in another format.

While there are extensive studies on metacognition carried out with experts and novices, with academically - disabled students (Slife, Weiss & Bell, 1985) and with young children (eg, Myers & Paris, 1978), there are insufficient studies carried out with youths from different academic backgrounds. This is important as knowledge gained in this area could provide teachers with some guidelines on what to teach to students with different academic backgrounds. There are a number of unanswered questions on the effects of academic settings on students' metacognition. For example, do students from different grade levels exhibit different amounts of cognitive knowledge? Do students from lower grade levels exhibit less frequent use of metacognitive skills such as monitoring, planning and verifying their answers when solving mathematics problems? What type of strategies do different grade-level students employ? Are the strategies surface type, deep, or achieving ones? Do students from different streams and different academic tracks exhibit different frequency of usage of metacognitive processes?

Objectives of This Study

This study investigates the metacognitive processes used by secondary school students in mathematics. Specifically, it seeks to answer the following questions:

- (1) How frequently do students employ metacognitive strategies during mathematics problem solving?
- (2) Do students from different academic settings (academic stream, academic tracks and grade levels) differ in their usage of metacognitive strategies?
- (3) Do students from different academic settings use different types of strategies (surface, deep or achieving strategies)?

Method

Subjects

Over 2500 students from nine secondary and four pre-university junior colleges participated in the research on learning and teaching strategies. The subjects were selected using the stratified sampling method. Within each category of schools and pre-university colleges, the schools were randomly selected and within each school, the classes of students from each stream, level and academic track, were randomly chosen. Whole classes were used in the survey and in each class, one third of the students was randomly assigned to answer the Language form questionnaire on learning strategies, another third answered the Science and Mathematics form, and the rest answered the Social Studies form.

Seven hundred and seven students answered the Science and Mathematics form. Out of this, 37 sets of data were incomplete thus leaving a sample size of 670. The 670 students came from

- (a) three streams, namely, Special Assistance Programme (SAP), Normal Stream and Express stream;
- (b) three grade levels (Secondary 2, Secondary 4, and Pre-U 1);
- (c) three academic tracks (Arts, Science and General).

Instrument

The instrument used is the Study Skill Questionnaire (Chang, 1988; 1989). There were three forms, each pertaining to the study of specific subject areas, namely, Language, Science and Mathematics, and Social Studies. Within each form, there were three sections in the questionnaire with the first two sections being common to all the three forms. The first two sections contained items on learning strategies, attitude towards learning and their motives for learning and they were drawn from the Learning Process Questionnaire (Biggs, 1987). The third section contained items that were specific to the content area. For example, in the Science and Mathematics

form, students were asked about the frequency of usage of metacognitive strategies in solving mathematical and science problems while in the Language form students were asked about their metacognitive strategies in reading comprehension and in listening.

This study reports only on the students' returns in the Science and Mathematics form and on the section asking students about their metacognitive strategies in problem solving. There were 20 items related to strategies used in mathematical problem solving and for the purpose of this study, the items were classified into five sections. The first four sections followed the cognitive-metacognitive framework suggested by Garofalo and Lester (1985) with four items in each component. The fifth section of items measured students' beliefs in strategies which would help them in problem solving.

- (i) ORIENTATION COMPONENT: The items here concentrated on the process of reading and understanding of the problem (eg, I analyse and try to understand the information given and draw inferences).
- (ii) ORGANIZATION COMPONENT: The items in this section concentrated on the approach and the planning for execution of procedures (eg, I turn an argument over in my mind a number of times before accepting it).
- (iii) EXECUTION COMPONENT: The items tried to determine how students execute the plan during problem solving (eg, I find that drawing diagrams helps me to solve problems).
- (iv) VERIFICATION COMPONENT: The items were directed at finding out how frequently various strategies were used to check answers and procedures (eg, I check over my test to avoid making mistakes).
- (v) BELIEFS: The items determined the beliefs students have concerning mathematics problem solving (eg I believe there is only one best way in solving a problem).

The questionnaire had been pilot tested, validated and used in a number of research studies (Chang, 1988; 1989).

Procedure

The questionnaire required students to rate each item on a 5-point Likert scale, with a score of 5 indicating a frequently-used metacognitive strategy while a score of 1 indicated a rarely-used or never-used strategy. The questionnaire was administered to the whole class by the class teacher. Most students were able to finish answering the questionnaire within a one-period lesson. The class teacher explained some phrasing of items to students who could not understand the item.

Results

There are five sets of subscores with a maximum of 20 points per set. There is a score for each of the four problem solving components (orientation, organization, execution and verification) and one score for students' problem-solving beliefs. Analysis of variance (ANOVA) at 0.05 level of significance was carried out using the mean scores as the dependent variable. Three separate analyses were conducted with different independent variables, namely, stream; level; and academic track. The results of each analysis are described below.

Stream

The three streams of Express, Normal and Special are applicable to secondary schools

only. Data from Pre-University students were not included in the analyses.

The means of all the problem phases were found to be statistically different. In all the four phases, Normal stream students scored lower than students from the Express and the SAP stream indicating that Normal stream students had reported less frequent use of metacognitive strategies than students from SAP and Express Stream students (Figure 1). A follow-up test using Duncan's test showed that the means of SAP students and Express students were not significantly different.

The score in the verification component was highest compared to the three other phases. The means for the three phases of orientation, organization and execution were around 12.5 while the means for the verification component were around 15.5.

Based on classification by Biggs (1987), each item in the questionnaire was classified as either surface, deep or achieving strategy. On the analysis of individual items, it was found that Normal stream students used surface strategies more often than deep or achieving strategies. For example, they reported that they used surface strategies like "I need to attend to the instructions carefully in order to get the required results" (mean = 3.57) more frequently than to deep strategies like "I analyse and try to understand the information and draw inferences" (mean = 3.03).

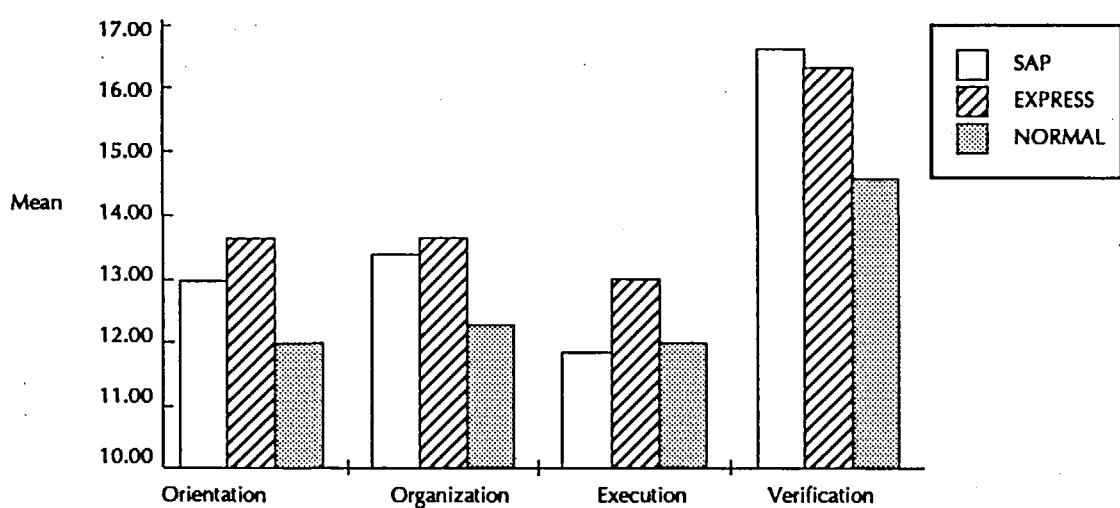


Figure 1: Means of each component by stream (n = 550)

Level

The means of each component are shown in Figure 2. Statistically, there was no difference in the frequency of usage of metacognitive strategies between students from different levels, viz. Secondary 2, Secondary 4 and Pre-U 2. Again, the means for the verification component (averaging 16.0) were higher than the means of the other phases (averaging 12.5).

Academic Track

The means of the four phases are shown in Figure 3 and the means were found to be statistically not different for all the three tracks. The means for the verification component were higher than the means for the other three components (averaging 13.0).

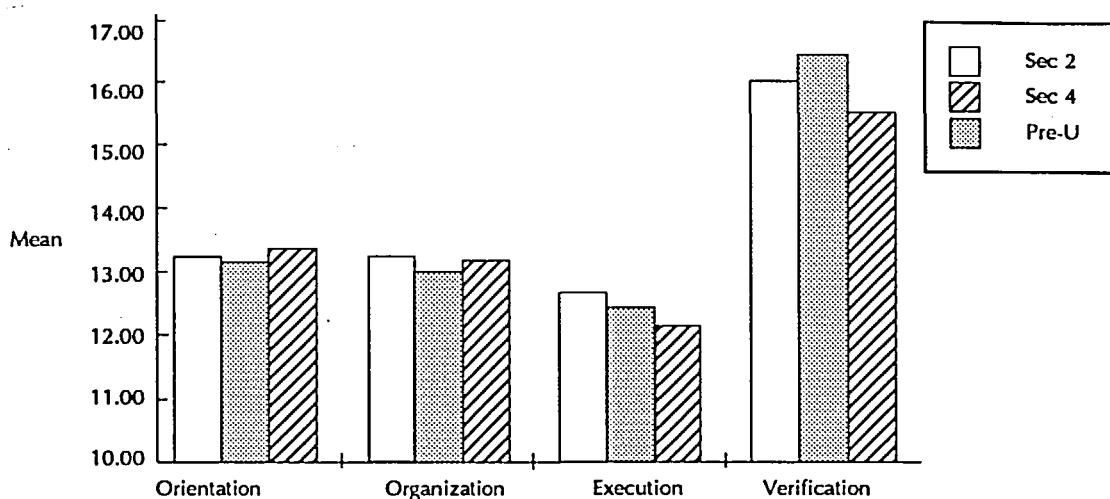


Figure 2: Means of each component by Level (n = 670)

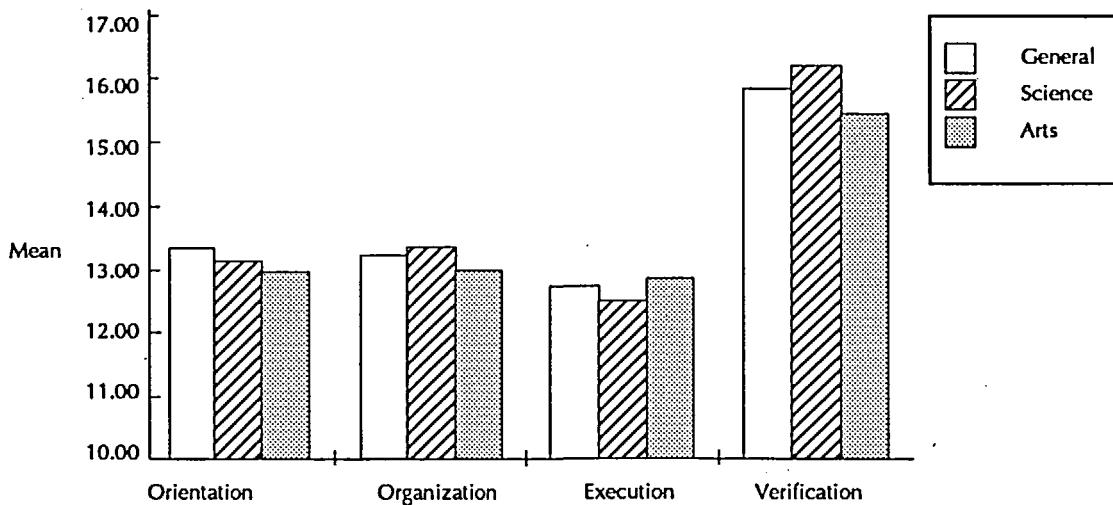


Figure 3: Means of each component by Academic Track (n = 640)

Beliefs

Students' problem solving beliefs were investigated through four items (17, 18, 19, and 20). Figures 4, 5, and 6 show the means of the four items for stream, level and academic track, respectively. Students from the Normal stream, from Secondary Two and from General and Arts academic tracks believed that certain surface strategies were appropriate for developing problem solving skills as shown in Item 20 where they indicated that they memorized model answers more often than the other students.

Similarly, in Item 19, more students from Secondary 2, Normal stream, academic track of Arts and General, believed that there is only one best way to solve a problem. On the other hand, the Express and SAP students, students from the General and the Arts stream, and Secondary 4 and Pre-University 2 students believed that certain deep strategies (eg, they needed a lot of drill and practice; that it is important to be able to solve problems set in past-year examination) are important to their problem solving abilities. This is indicated by the higher ratings in Items 17 and 18.

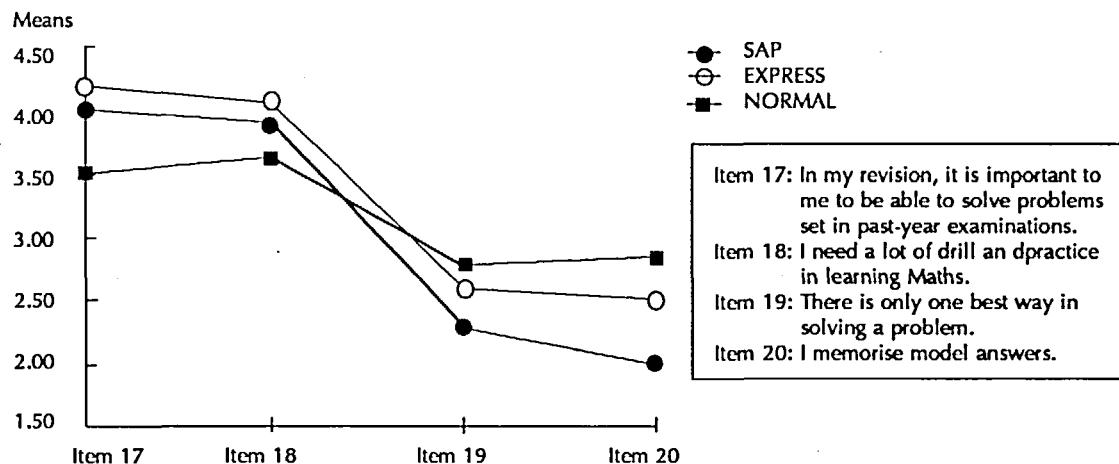


Figure 4: Means of Metacognitive Beliefs by Stream

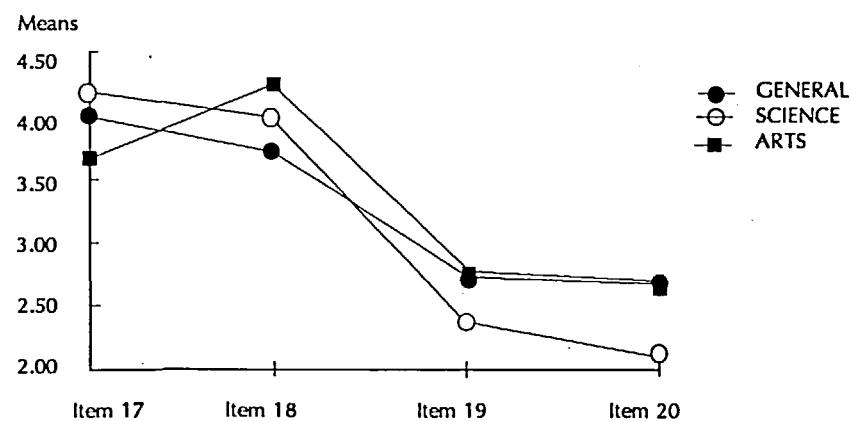


Figure 5: Means of Metacognitive beliefs by Academic Track

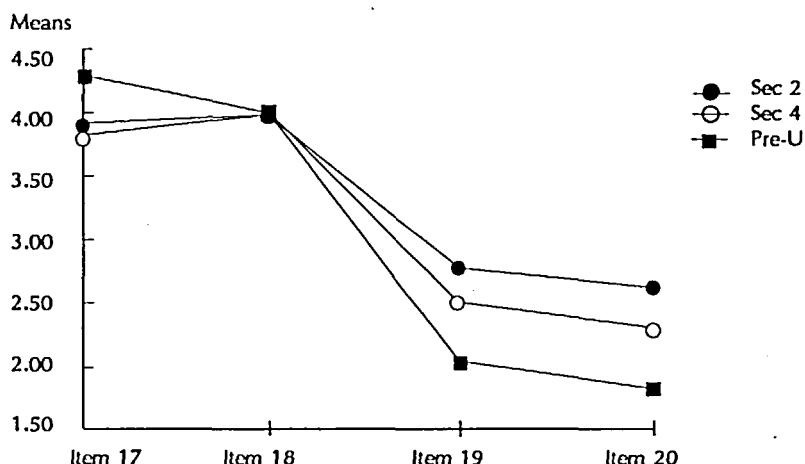


Figure 6: Means of Metacognitive Beliefs by Level

Discussion

The results show that the mean scores for the four components are above the half-way mark of 10 indicating that students are conscious of metacognition and that they used strategies for monitoring and regulating the processes necessary for problem solving. Most students indicated that they practiced some of these metacognitive activities at least half the time when they are solving problems. Although the four components are equally important for problem solving, the students practice the verification process more frequently than the other components.

This is indicated by the high scores for all the four items in the verification component. However, the four items of the questionnaire asked students on only one aspect of the verification component. The students were asked about the accuracy of their workings and the accuracy of their answers. This aspect of verification is emphasized during classroom instruction and hence, the high scores. Unfortunately, the questionnaire is unable to give us an insight about what really happened in their monitoring process during problem solving. A better method would be to use protocol analysis, interviews and observations as additional sources of data collection.

Although the results generally showed that students do practice metacognitive activities, certain groups of the student population were not very fluent in their usage. For example, the Normal stream students scored lower when compared to the SAP and Express stream students. This could be due to the selection process when students were streamed into SAP, Express or Normal. The Normal stream students follow a five-year secondary school education programme compared to the Express and the SAP stream students who follow a four-year secondary school programme. The students entered the various streams based on the achievement scores in their Primary School Leaving Examination. Thus academic ability could have an effect on the frequency of usage of metacognitive strategies and other researchers have reported similar findings (Chang, 1989; Peterson, 1988; Slife et al, 1985). Also, the methods used in the teaching of students from different ability groups could have caused the differences in the frequency of usage of metacognitive strategies. It has been reported that high-ability students preferred less structured instruction; instructions that were inductive rather than deductive; methods which required them to self-learn (Snow & Lohman, 1984) and these teaching methods employed by teachers could have encouraged the development of

metacognitive skills. On the other hand, lower-ability students preferred instruction to be highly structured, deductive rather than inductive and more focused on content and these methods are not conducive to the development of metacognitive skills. It appears that academic ability influences metacognition in three ways: first, the lack of academic ability impedes students' knowledge of strategies; second, the lack of knowledge of metacognition leads to poor academic performance and third, the teaching styles used can discourage or encourage the development of metacognitive skills. Unfortunately, findings from this research cannot differentiate between them.

Age and years of schooling are some other factors that could influence one's knowledge and application of metacognitive strategies. Awareness of metacognitive strategies starts at a very early age. Various studies on metamemory have shown that children as young as five years old are aware of strategies for recall (see Flavell & Wellman, 1977). It is also observed that older children are better at using various strategies for recall than young children (eg, Brown, 1978). This is also true in reading comprehension. Myers and Paris (1978) found out that 12 year-old students were more aware of the effects of various variables, such as their knowledge of content and their interests in the stories, on their comprehension than 8 year-old students. Biggs (1987) in his study, noticed that young students may have the awareness of the needs of monitoring and regulating their cognitive processes but may not have sufficient executive control over them. However, in this study there was no statistical difference in scores between students of different ages as students from Secondary 2, Secondary 4 and Pre-U 2 indicated similar frequency of usage in the four components. While the level of usage remains the same across students from different levels and academic tracks, the types of strategies used differed. The younger students, the Arts and General track students and Normal stream students tended to use more surface strategies. However, the use of surface strategy should decline as the level changed to the higher level. Similar observations were also noted by Biggs

(1987). This study does support the fact that students become increasingly more aware of metacognition with increasing years of schooling.

Research Implications

Research on metacognition should be a multifaceted task using a variety of research methods, instruments and a sample with different academic backgrounds. This study is the initial phase of the research project on effectiveness of learning strategies and is based on students' self report in a questionnaire. However, the use of self-report questionnaire has its limitations. Ideally, this report should be supported with evidence from interviews and verbal protocol. These procedures would give us a better insight of the type of problem-solving and metacognitive activities used. Unfortunately, there are limitations to this procedure. This research method is time consuming and only a handful of students can be interviewed. In Singapore where students are not very vocal, gathering data using this method is problematic and students have found this method to be unnatural, mentally demanding and difficult as they find it difficult to verbally express themselves (Wong, 1990).

Teaching Implications

This study shows that students need guided instruction in the use of metacognitive strategies for problem solving. Besides, the emphasis on verification of solutions, the students reported less frequent use of monitoring strategies in planning, executing and orientation. Teachers should therefore consider incorporating strategies to help students develop metacognitive skills in these three areas. Generally, teachers do not introduce metacognition as a topic in a lesson but instead subsume the concept of metacognition within the lesson content. Thus, to the students metacognition is not taught explicitly and the concept of metacognition could be lost amongst the more important subject matter. Instead, there should be conscious and direct effort by the teachers to introduce the

concept of metacognition during the lesson. Students need to be informed of what metacognition is, how it works, when it works and be provided with some examples. At present, at the teacher training level, trainee teachers are exposed to a number of lectures on this aspect. They are encouraged to use various methods to achieve this. They could incorporate some of the teaching methods, activities, and approaches suggested by Callahan & Garofalo (1987), Long (1986) and Devine (1981).

Drawing from this study and other reports, lower ability students do not use strategies for metacognition as frequently as high ability students and this deficiency could lead to poor performance. They, therefore, need extra training in order to enable them to operate at the same level as the higher ability students. Various projects on teaching students thinking skills, reading skills and learning skills have been very successful. For example, Peterson and associates (cited in Peterson, 1988) conducted an extensive project which helped fourth grade students to develop thinking skills in mathematics, and noted that low ability students benefited more from the training. She said "the thinking skills training may have provided the low ability students with the thinking skills or cognitive strategies that they did not have, but that higher ability students did have already.... Acquisition of these strategies then permitted them to learn

as effectively as the higher ability students within the class" (p. 10). Attempts have been made by schools and the Ministry of Education to introduce some of these projects to students. Some examples include: the publication of a handbook, *Learning Skills in Content Area*, for secondary school teachers to be used for conducting workshops on learning skills, the introduction of DeBono's CORT programme to 25 secondary schools, and training programmes to student-teachers on effective teaching and learning skills.

Conclusion

This study reports on the frequency of usage of metacognitive activities and the type of strategies used by students from different academic settings in mathematical problem solving. It is generally observed that students are aware of metacognition although students from the Normal stream seem to use strategies on metacognition less frequently. There is a declining use of surface strategies and increasing use of deep and achieving strategies as the level changed to the higher level. The results of this study warrant a need to introduce the teaching of metacognition to all students especially to low ability students.

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Metacognition in schools: what does the literature suggest about the effectiveness of teaching metacognition in schools?

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Metacognition in schools: what does the literature suggest about the effectiveness of teaching metacognition in schools?

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ABSTRACT

This paper focuses on a neglected area of school policy and practice: metacognition. As education becomes increasingly evidence-informed policy makers, school leaders and teachers are becoming increasingly research literate and have ready access to an ever-growing range of evidence about 'what works' in schools. Influential sources of evidence, such as the Education Endowment Foundation's Teaching and Learning Toolkit, often indicate that teaching metacognition in schools can have a very positive effect on pupils' outcomes. In this paper, we examine over 50 studies to ascertain the effect of teaching metacognition in schools on pupils' outcomes and their wellbeing. Following our review it is clear that there is strong evidence indicating the when metacognition is effectively taught in schools then there is a very positive effect on pupil outcomes; there is less evidence about the relationship between teaching metacognition and pupil wellbeing, but the evidence which does exist is also very positive. Having identified that teaching metacognition can help improve pupil outcomes in schools, we then pose questions about the English government's attitudes towards evidence-based practice. We ask why the government adopts some policies and strategies which have an international evidence base, while not adopting other policies or strategies which have at least an equally strong evidence base. This paper concludes by suggesting how policies and practices can be improved in schools, Initial Teacher Education establishments and at the level of national policy.

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Introduction

Teaching is becoming an "evidence-informed profession" (DfE 2016a, 37). There is a growing cultural acceptance that teaching is more complex and sophisticated than simply transmitting knowledge, which is leading to vigorous, informed discussions about "what works". Such discussions are supplanting the old debates, such as "traditionalist" versus "progressive" education, or quantitative versus qualitative research, although these still rumble on in the Twittersphere. This is slowly encouraging an environment where practitioners and policy makers are becoming increasingly research literate and confident about identifying

high-quality research. This, in turn, means that professionals are able to make up their own minds about what is most likely to work best in their own contexts. We are writing in the context of the English education system, where the emerging “evidence-friendly” environment is fostered by organisations such as the Education Endowment Foundation and the Chartered College of Teaching, as well as the government itself. It is in this context that we examine what the evidence suggests about one particular strand of pedagogical practice: thinking skills, also known as metacognition.

The reason for focusing on metacognition as a specific strand of pedagogical practice is simple. Multiple studies make strong claims that when children are effectively taught metacognitive skills, they tend to make better progress than children who are not taught such skills. In this paper we will examine the evidence for such claims by reviewing much of the key literature from the last 20 years. We are seeking to answer one main question:

- What does the literature suggest about the effects of teaching metacognition in schools?

To help investigate this question we seek to answer four sub-questions:

Question 1: What does the international literature suggest about the effectiveness of metacognition on pupil outcomes in classrooms?

Question 2: What does the literature say about the relationship between metacognition and particular groups of pupils?

Question 3: What does the literature say about the relationship between metacognition and pupil wellbeing?

Question 4: What are the implications of what the international literature says about these questions for educational policy?

These are important questions because, as this paper will demonstrate, very strong evidence exists indicating that the effective teaching of metacognitive skills can make a significant difference for pupil outcomes. However, there is little to suggest that schools are using such strategies in any widespread manner, and metacognition is not promoted by the English Department for Education (DfE), while it does promote other strategies. Such a situation raises broader questions, such as why some strategies are championed by practitioners or policy makers, while others remain on the shelf. This paper begins to address these issues and indicates where further research or work is required.

A relatively conventional structure has been adopted for this paper. Initially we define our terms and present our methodology. The central literature review section of this paper seeks to answer the first three sub-questions, focusing on what the international literature says about metacognition in schools. Following the review of the literature, we identify some of the limitations of our work. We then offer our interpretations of how policies could be altered to re-vitalise the teaching of metacognitive skills in classrooms; in this section we offer our tentative answers to Question Four. Our conclusion offers answers to the main question, “What does the literature suggest about the effects of teaching metacognition in schools?”.

In the following section we define what we mean by “metacognition”, locating it in the wider context of contemporary schools and school systems. As noted above, we are writing in the context of the English education system, but we are very conscious of the international environment; this helps to shed some light on English policies and practices.

Definitions and context

Metacognition, or “thinking about thinking”, is well established as an internal, psychological process necessary for effective learning and problem solving (Flavell 1979). The concept has been extensively written about, with different theorists and writers adopting differing definitions. For the purposes of this paper we will use the definition offered by the Organisation for Economic Co-operation and Development (OECD), which states that metacognition is,

...a second or higher-order thinking process which involves active control over cognitive processes. (Mevarech and Kramarski 2014, 36)

The majority of researchers separate metacognitive knowledge from metacognitive skills (e.g. Veenman, Hout-Wolters, and Afflerbach 2006). Thus, there is a difference between knowing about metacognition and being able to successfully employ such skills to complete novel tasks. In addition to this, we accept the three level model suggested by Donker et al. who recognise “an interaction of cognitive, metacognitive and motivational processes, which work together during information processing” (Donker et al. 2014). Various studies make strong claims for the significance of metacognition on pupils’ learning. Veenman and Beishuizen, for example, suggest that metacognition accounts for roughly 17% of a child’s ability to be successful at school, while intelligence accounts for approximately 10%. This is a significant statistic, reinforced by other studies (e.g. Muijs et al. 2014) which clearly suggests the necessity for schools to teach metacognitive skill effectively.

We have chosen to use “metacognition” as an overarching term, encompassing other commonly used terms, such as “self-regulated learning”, “thinking skills”, and “Learning to Learn” (L2L). There are also the skills which have become generically known in some business sectors as “twenty-first Century Skills” (Voogt and Roblin 2012), although these often form a broader framework of skills than the higher-order thinking skills which are the specific focus of this review. Twenty-first century skills often include metacognitive skills, but they also tend to include a broad range of IT and communication skills (Laar et al. 2017). While we fully accept the importance of such skills, especially in contemporary workplaces, they are largely tangential to our study, and thus do not form a significant part of our research.

We recognise that metacognition is a “fuzzy” concept (Akturk and Sahin 2011; Bassey 2001) and that a number of related terms are contested (Proust 2010). However, the central aim of this paper is to understand the effects of using and assessing metacognitive skills in classrooms with a view to improving children’s outcomes. As such we have attempted to be as inclusive as possible about approaches that have been shown to make a difference, and fall within the scope of what we consider to be metacognitive strategies.

Because metacognition has such a fuzzy quality, there is no agreed typology of metacognitive strategies used in classrooms (cf. Pintrich 2002). However, most educators would include strategies that help pupils to monitor, plan, evaluate and regulate their performance whilst completing a particular task, as well as strategies that consciously help pupils solve novel problems. These could include, for example, writing frames (Myhill and Newman 2016), Mind Maps (Buzan and Buzan 2000), concept maps (Hay and Kinchin 2006) or any other taught strategies which seek to equip pupils with an increased understanding of how to learn, as opposed to an increased knowledge specific to a subject domain. The key thing is that pupils can use such strategies in a controlled, conscious way to solve novel problems.

Methods

This paper employs Systematic Literature Review (SLR) techniques suggested by Cooper (2010) to identify relevant search terms and literature databases. ERIC, SAGE Journals Online, Taylor & Francis Online and PsycINFO have been used as the principle databases, and they were trawled between February 2017 and March 2017. Articles were limited to English language, peer-reviewed and published between 2000 and 2017. Following initial searches, further filters were added so that the search was refined to focus on schools, school-age children or teachers. Articles for inclusion in this report were selected following abstract analysis, resulting in 51 core studies. These included:

- Quantitative Studies: 29
- Qualitative Studies: 2
- Literature Reviews: 15
- Meta-analyses: 3

An additional range of relevant texts providing helpful historical and policy contexts have also been used in this paper. Several texts were excluded from this report, as they did not reach the threshold for high-quality research; this was typically because the methodology was judged to be relatively weak, or there was judged to be a conflict between the size of the research sample and the strength of the claims being made.

In the next section of this paper, we will place metacognition in its historical context, before discussing the policy context of metacognition in schools. We will then move onto the deeper analysis of what recent research suggests about the use of metacognition in schools.

Metacognition in historical and policy contexts

The development of metacognition as a helpful way to understand learning is most widely attributed to the pioneering work of John Flavell (1979), who built on the work of Vygotsky (1978) and in particular the concept of the Zone of Proximal Development (ZPD). Following Flavell, the study of metacognition focussed on the field of psychology. This focus has since broadened to include other fields, including education. Quickly a consensus emerged that children who develop effective metacognitive skills are more likely to become successful learners than children who hold less effective metacognitive skills. In England, at least, this led to a growing interest in the use of metacognition across education. Various commercially available programmes designed to improve students' metacognitive skills were developed, such as the Cognitive Acceleration programmes originating from King's College London (Let's Think 2017), the Somerset Thinking Skills Course (Blagg 2017) and Building Learning Power (Claxton, Chambers, and Lucas 2011). Although the dates of such programmes appear relatively contemporary, they each have their roots in the 1980s or 1990s. Such commercially available programmes did not gain significant traction in schools, despite the strong evidence base underpinning them. One of the reasons for this lack of take-up could well be that metacognition has not been a formal part of either the National Curriculum in England, nor a part of the recognised metrics used for accountability purposes. School leaders, understandably, tend to focus on things which are mandated or measured, and thus side-line other strategies which might be felt to be "nice-to-have", rather than essential. The evidence

suggests that such a view is short-sighted. As this paper demonstrates, metacognition can help to significantly improve pupil outcomes, but the pressures which school leaders face are understandable.

However, although there was no explicit requirements for schools in England to use metacognitive strategies the Labour government of the 2000s did develop a national strategy for Personal, Learning and Thinking Skills (PLTS) (QCA 2009). Recognising the value of six groups of skills for employers, this policy aimed to develop children who would become:

- Independent enquirers
- Creative thinkers
- Reflective learners
- Team workers
- Self-managers
- Effective participants

The aim was for schools to teach children to develop these skills in children aged 11–19, and it was envisaged that the PLTS policy would be integral to the ultimately doomed Diploma qualifications. Yet, the PLTS framework was side-lined by the newly elected Coalition Government from 2011, along with the Diploma qualifications; although it still exists in the field of apprenticeships, it is rare to find schools utilising PLTS (Braun, Maguire, and Ball 2010). It should not come as a surprise that the PLTS framework became associated with the apprenticeship movement when one considers the degree of overlap between this framework and the so-called twenty-first century skills referred to above, which are generally supported by industry. What is more surprising, in some ways, is the willingness of the government to side-line this framework when it so clearly supports schools to help prepare young people for the world of work. There is a possibility that a version of this framework could be revitalised with the recently announced Technical Level initiative (Boles 2016), which we will discuss later in this paper, but the government is surprisingly quiet about metacognition.

The government's lack of engagement with metacognition is all the more surprising when one considers the willingness of the English government to adopt policies and practices from countries and jurisdictions that traditionally do well in the PISA tests. Programmes such as Shanghai Maths, for example, have been heavily promoted by ministers (Gibb 2016). Something that receives less attention, however, is the extent to which high-performing school systems, including Shanghai, Hong Kong and Finland teach metacognitive skills across their schools (Cheng and Wan 2017; Retna 2016; Vainikainen, Hautamaki, et al. 2015; Vainikainen, Wustenberg, et al. 2015; Yeung 2015). Shanghai has been developing approaches to "Design Thinking" (Retna 2016), which encourages students and teachers to engage with academic work using creative strategies typically associated with the design industry. Hong Kong is encouraging schools to adopt critical thinking approaches to classroom activities (Cheng and Wan 2017) as well as Higher Order Thinking skills (Yeung 2015). Finland has also put considerable effort into the development of thinking skills across the curriculum (Vainikainen, Hautamaki, et al. 2015; Vainikainen, Wustenberg, et al. 2015). This raises interesting and important questions about the reasons for the promotion and adoption of some strategies that are used in high-performing school systems over others. This also raises linked questions about the government's reasons for adopting some strategies, which appear to be rooted in strong evidence, whilst not adopting other strategies, which appear to be rooted in equally strong evidence. We will discuss this issue later in this paper.

Other parts of the UK appear to be adopting a different approach. The Welsh Government, for example, has identified that their curriculum requires modernising, and that, "The case for fundamental change is powerful." (Donaldson 2015, 11). There is a growing concern that the current system in Wales is not providing all children with the opportunities to become successful, twenty-first century adults (Hopkins 2016; OECD 2014) and that the Welsh system is unsuccessfully attempting to balance the competing pressures of preparing children for an increasingly complex society, with meeting increasingly stringent accountability measures (e.g. Ball 2013). Such concerns have led to the development of a new, evidence-based curriculum for Wales, intended for full implementation over the coming years (Welsh Assembly 2015).

Having established the historical and policy contexts of metacognition in schools, we now turn our attention to reviewing what the literature says about the effectiveness of teaching metacognition in schools.

In the following section of this paper, we explore what the literature suggests about the effects of teaching metacognition on pupils' outcomes, where outcomes primarily refers to academic progress data. Strong evidence, derived from rigorous primary research, indicates that having metacognitive knowledge coupled with the ability to use metacognitive skills is a very effective way of predicting successful learning (Chang et al. 2012; Ellis, Bond, and Denton 2012; Lai 2011; Stel and Veenman 2008; Zumbrunn, Tadlock, and Roberts 2011). Although some contest the role of metacognition (e.g. Kozulin 2011), a growing range of research indicates that metacognition is central to improving learning outcomes across age ranges and across school subjects (Baas et al. 2015; Dignath, Buettner, and Langfeldt 2008; Donker et al. 2014; EEF 2016a; Hattie 2016; Perry, Albeg, and Tung 2012).

We begin by discussing three of the most well-known projects which have attempted to synthesise the findings of various primary research programmes (Dignath, Buettner, and Langfeldt 2008; EEF 2016a; Hattie 2016). Much of the discussion revolves around the different effect sizes which different sets of authors identify for different strategies. We will then move on to examine single studies to understand what they suggest about the effects of teaching metacognition in schools. Broader attitudinal effects, such as wellbeing and motivation are explored later in this paper.

Metacognition and pupil outcomes

In the UK the Sutton Trust-Education Endowment Foundation Teaching and Learning Toolkit (EEF 2016a) is becoming an influential resource for practitioners and policy makers (DfE 2016a). Most of their evidence is taken from quantitative studies, which allows the EEF to calculate effect sizes; however, this does exclude qualitative studies as well as introducing potential research biases (EEF 2015; Katsipataki and Higgins 2016), and raising the issue of the role of Randomized Control Trials in education research. The EEF strongly favours the use of RCTs in its funded research, and this methodology has gained significant traction in the minds of policy makers. However, there is significant concern about the extent to which RCTs can explain the direct causes of effects and thus improve student outcomes in predictable ways which are replicable across multiple contexts (Biesta 2010; Thomas 2016). Such concerns raise multiple issues, both for the current paper and the ways in which educational policy in England is influenced. Regarding the first issue, we have deliberately chosen not to rely on studies that are dependent on RCTs. Rather, as described above, we have reviewed

as much of the international literature as possible, including qualitative studies, so that we could include “everything we’ve got.” (Thomas 2016, 406). We will return to the second issue later in this paper.

Taking such caveats into account, the Sutton Trust-EEF Toolkit indicates that metacognition is a relatively highly effective and efficient approach for improving pupil outcomes, with a mean effect size of .62 (EEF 2016b), typically adding approximately eight month’s progress. The “Toolkit” succinctly displays three elements for each strand; these are the cost, the strength of available evidence and the impact. Taking these three elements into account it becomes clear that metacognition is amongst the very best performing strands of the EEF’s Teaching and Learning Toolkit. Metacognition is identified as very low cost, with very strong supporting evidence and an impact equivalent to adding eight month’s progress.

The work of the EEF draws upon several studies, including Dignath et al.’s (Dignath, Buettner, and Langfeldt 2008) rigorous meta-analysis of research carried out with primary school pupils. Through their research, they identified three concepts with an average effect size of .69 for those pupils who had been trained in metacognitive strategies:

- Academic performance .62
- Cognitive and metacognitive strategy use .73
- Motivational aspects .76

This indicates that the effect sizes are relatively high, although the authors suggest that effects on academic performance in specific subjects are more difficult to predict, with the clearest signs of a positive impact of metacognition found in mathematics education (Dignath, Buettner, and Langfeldt 2008, 118); this view is shared by more recent research (Sahin and Kendir 2013). When academics turn their attention to the teaching of science, similar outcomes are observed (Zohar and Barzilai 2013), leading some to the conclusion that metacognition is most effective when used with mathematics or science. However, when research is conducted to specifically explore the cross-curricular impact of metacognition (Mannion and Mercer 2016; Perry, Albeg, and Tung 2012) these data suggest that metacognition has a much wider applicability. Indeed, it is fair to say that the evidence suggests that teaching and learning metacognitive skills and knowledge can add value across the whole curriculum. Wherever metacognitive skills are taught in lessons, there appears to be improvements in pupil outcomes, irrespective of which subjects are being taught.

John Hattie’s *Visible Learning* (Hattie 2016) project is perhaps the most ambitious, and well-known, meta-analysis of research studies attempting to quantify how much difference specific strategies make in the classroom. His most recent work indicates that metacognitive strategies have an effect size of 0.53, which is broadly in line with both the EEF and Dignath et al. However, he also indicates that other strategies which can be broadly considered to be in line with metacognitive methodologies also have significantly positive effect sizes, such as “Self-Questioning” (0.64 effect size) and “Problem solving” (0.63 effect size). The *Visible Learning* project also examines research about different forms of assessment which link with metacognition, as will be discussed below.

The positive effects of teaching pupils metacognitive strategies are echoed by other classroom-based studies in differing contexts (e.g. Baas et al. 2015; Mannion and Mercer 2016; Stel and Veenman 2008; Veenman, Hout-Wolters, and Afflerbach 2006). One of the most prolific academics to study metacognition is Marcel Veenman who has extensively

studied the relationship between metacognition and intelligence. Over a period of nearly 20 years, Veenman and his colleagues have studied children and young people in a variety of contexts from primary schools to universities. Using sophisticated quasi-experimental techniques, rooted in quantitative methods, Veenman is able to make a number of strong claims about metacognition. A central claim is that metacognition can be successfully taught from primary school level to university level (Stel and Veenman 2008, 2010; Veenman and Beishuizen 2004; Veenman and Spaans 2005; Veenman, Hout-Wolters, and Afflerbach 2006). Another claim is that in order to maximise the impact of the teaching, several conditions need to exist. First, metacognition should be embedded across the curriculum, rather than taught in discrete "metacognition lessons"; second, the purpose of the learning, including the metacognitive element should be clearly explained to the pupils; and thirdly, the learning should be extended over a long period of time (Veenman and Beishuizen 2004, 635). They also conclude that metacognition is a strong predictor of academic performance, implying that there is a strong relationship between the two (Veenman, Wilhelm, and Beishuizen 2004). This view is reinforced by Hattie (2013), who suggests that pupils are very clear about their own academic performance when taught appropriate skills of metacognition.

Another key element of successfully teaching metacognition is the successful utilisation of group work in schools. This makes sense, as many elements of metacognition involve social-cognitive theories (Dignath, Buettner, and Langfeldt 2008; Mannion and Mercer 2016). This has implications for classroom practice, as Dignath et al. note; to work successfully in groups, children must first learn how to work successfully in groups. This, in turn, has implications for Initial Teacher Education programmes as well as Continuing Professional Development programmes in schools. Dignath et al. suggest that this might be a particular issue for primary school teachers (Dignath, Buettner, and Langfeldt 2008, 121). Yet when this is successful, the effect size of small group work can be significant (Hattie 2016) at 0.47.

Turning our attention to assessment, Baas et al. (Baas et al. 2015), explicitly studied the relationship between metacognition and Assessment for Learning (AfL) (Wiliam 2011), with AfL typically meaning that teachers are using a combination of the following strategies:

- clarifying and understanding learning intentions and criteria for success
- engineering effective classroom discussions, questions and tasks that elicit evidence of learning
- providing feedback that moves learners forward
- activating students as instructional resources for each other, and
- activating students as owners of their own learning (Wiliam 2006)

Baas et al. found that the effective use of metacognitive strategies both supported and developed the effectiveness of AfL strategies, thus accelerating learning in a virtuous spiral. It would appear that when pupils are taught how to learn, through metacognition, in conjunction with accurate formative assessment, through AfL, the potential for academic success is high. Baas et al. found the following effect sizes,

- Monitoring & task orientation .25
- Monitoring & planning .26
- Scaffolding & surface learning strategies .25
- Scaffolding & deep level learning strategies .32
- Scaffolding & process evaluation .36

This is reinforced by Hattie (2016). Although AfL is not treated by Hattie as a discrete strategy, many of the strategies which his project studied are in line with the principles of AfL, and many of these have significantly positive effect sizes. These include questioning (0.48), self-questioning (0.64), providing formative evaluation (0.68), feedback, (0.73) and reciprocal teaching (0.74). The Teaching and Learning Toolkit (EEF 2016a) reports similar impacts for some strategies, such as Feedback and Peer tutoring. It should be noted that there is research which suggests that the effect of feedback, for example, is more highly thought of by teachers than by students (Havnes et al. 2012), but the majority of evidence very strongly indicates that AfL is central to effective learning and teaching.

Thus, following a review of available research it is fair to suggest that teaching metacognitive knowledge and skills has a positive impact on pupils' outcomes, at least in terms of academic progress and attainment. Having illustrated that metacognition has a positive effect on pupil outcomes at the school level, we now turn our attention to pupil-group level.

To date there is little research examining the relationship between metacognition and specific groups of children. Most of the research has focused on the effects of the learning programmes themselves, and has not examined the details of any differences between learners from different groups. There is limited, but strong, research (Pat-El, Tillema, and van Koppen 2012) suggesting that metacognitive strategies are effective across different ethnic groups. In their study of first and second-generation immigrant children in the Dutch education system, the authors found that there was little difference between the ways in which children from minority ethnic groups and indigenous children valued teaching strategies, specifically feedback and scaffolding techniques. There is also emerging evidence that metacognitive strategies are effective for pupils with challenging behaviours in mainstream schools (Burgess 2012). Perhaps this should not be surprising, as most strategies which give children increased self-regulation will help them to become more successful learners.

The evidence regarding the impact of using metacognitive strategies with children from different socio-economic groups is also limited. It is widely accepted that socio-economic status (SES) is a major influence on a child's academic performance. Hattie, for example, attributes SES with an effect size of 0.54 (Hattie 2016), while "Home environment" has an effect size of 0.52 and "parental involvement" has an effect size of 0.49. One of the few studies to explicitly focus on the effect of metacognitive skills on children from low SES groups, Mannion and Mercer's (2016) work explores the effects of a "learning to learn" curriculum in one English secondary school. Using a range of assessment measures, including Cognitive Ability Tests (CATs) score, this study concluded that the strategic employment of a whole school curriculum rooted in metacognition improved outcomes for all students, which is in line with other research. However, this study is significant because it provides relatively strong evidence that teaching metacognition skills not only narrows the attainment gap between Pupil Premium students and non-Pupil Premium students, but actually reverses the gap (Mannion and Mercer 2016, 263). It should be noted that this is a relatively small study, focusing on a single, small secondary school and that further research is required to assess the generalisability of this result. However, the evidence is both strong and compelling.

There is also some research which indicates a positive relationship between pupils feeling good and achieving well at school (MacLellan 2014), as well as research indicating a strong correlation between pupils' sense of confidence and their outcomes (Stankov, Morony, and Lee 2014). These projects suggest that pupils' confidence can be increased by the successful,

autonomous use of metacognitive strategies, which is perhaps unsurprising. Some of the research previously referred to in this paper examines motivational aspects of metacognition, such as Dignath, Buettner, and Langfeldt (2008) who suggest that motivational aspects of pupils' experiences at school have an effect size of 0.76 which is highly significant. There is also sophisticated research demonstrating a strong link between pupils' abilities to overcome challenges and their wellbeing (Waaler et al. 2013). The most well-established research concerns the relationship between metacognition and motivation (see Karaali 2015, for a useful review of the literature), which generally suggests that there is a symbiotic link between the two: greater motivation leads to improved metacognition, which leads to greater motivation, and so on.

However, a note of caution should be sounded here as little of this research has been carried out in classrooms, with most of the research being laboratory based. Given the positive link between motivation, metacognition and attitudes which has been established in experimental studies, it makes sense that the relationship between these three elements would be fruitful research topics.

Limitations of this study

Thus far, we have presented what current research suggests about the effects of teaching metacognition in schools. It is clear that the majority of studies indicate that teaching metacognition in schools has a positive impact on pupil outcomes and pupil wellbeing. There is a smaller evidence base about the relative effects of teaching metacognition with particular groups of students, but where there is evidence, this also indicates a positive relationship between teaching metacognition and pupil outcomes.

It should be noted that there are several potential limitations to this review of the literature around the use of metacognition in schools. One of the biggest challenges for those involved with metacognition in classrooms is how to measure it. While there are numerous tools which can be used, including IT systems, (Nunes, Nunes, and David 2003), questionnaires (Dignath, Buettner, and Langfeldt, 2008), and inventories (DeLuca and Lari 2013; Ozturk 2017; Schraw and Dennison 1994) these all "entail limitations" (Baas et al. 2015, 43). The main problem is that most tools rely on self-reporting; self-reporting is not necessarily the most reliable strategy to use with adults, let alone children in classrooms. This raises many issues, not the least of which is that it is very difficult to measure metacognition in action (Georghiades 2004). This has led some to suggest that,

Presently, it is still impossible to establish causal relations between metacognitive instruction, (changes in) metacognitive knowledge and skills, and learning outcomes. (Muijs et al. 2014, 240)

and that "the need for [reliable] tools to measure metacognition continues" (Akturk and Sahin 2011, 3735).

Yet this paper has discussed many articles in terms of "suggesting" relative strengths of data and conclusions, rather than describing absolute causalities. It is not being claimed that the use of metacognitive strategies will always lead to improved outcomes and attitudes for all pupils in all schools. What we are suggesting is that there are numerous studies presenting evidence, which we find convincing, that when metacognitive strategies are carefully used in classrooms, then most pupils will be able to improve their academic performance; this, in turn, makes most pupils feel better and leads them to be more motivated in the future.

What is also being suggested is that a priority for future research should be the development of rigorous, effective evaluation tools which can be used by teachers in classrooms to measure the impact of metacognitive strategies. At least two types of research tool should be developed: one which can measure metacognition in action; and one which can measure the longer term impact of metacognition.

Implications for school curricula, school leadership and Initial Teacher Education

This paper has demonstrated that there is wide agreement that metacognition has great potential to equip children to become successful learners. Metacognition is an inherently human characteristic, which allows people to solve novel problems in different contexts and is of particular usefulness in classrooms. It appears that teaching any subject can benefit from the use of metacognitive strategies, and it also appears that such potential exists across all age ranges. This begs several important questions about school curricula, school leadership and Initial Teacher Education.

School curricula are becoming increasingly focused on ensuring the progress of pupils is maximised in ways which align with school accountability measures, such as Progress 8 in England for example, and it appears that teaching is becoming increasingly content-centred. Thus, although there is very strong evidence that metacognition is related to better than expected pupil performance, the Teachers' Standards (DfE 2011) which operate in England do not explicitly mention metacognition or any related aspect. Such a situation appears to put the government in an awkward position. On one hand they call for an "evidence-informed" profession (DfE 2016a), and recent guidance for Continuing Professional Development (DfE 2016b) states that CPD should be rooted in robust evidence. There is also a movement led by the Secretary of State for Education to strengthen Qualified Teacher Status (QTS) and to ensure that enhanced professional development acts as a "golden thread" through every teachers' career (Greening 2017b). In her vision for the profession, Justine Greening stresses that teachers should be "constantly seeking to improve teaching methods, use evidence, to look at research and stay ahead of the curve." (ibid.). Yet, on the other hand, it would appear that only particular types of evidence are championed and actively encouraged. While the government has been keen to promote the "Shanghai Maths" approach, for example, it should also be remembered that high performing school systems, including Hong Kong, Shanghai, Singapore and Finland, all include metacognition in their school curricula. There is also a clear favouring of strategies such as Randomized Control Trials (RCT) in education research, as discussed above. Yet it has been shown many times that such approaches are not appropriate for research into education; such a positivist approach may be attractive to politicians seeking votes and value for money, but education is intensely influenced by contexts. Thus, despite the clear and convincing evidence about the potential of metacognition and self-regulation to help improve pupil outcomes, and the fact that such strategies are integral to high-performing school systems, they are currently absent from the English government's priorities for education.

There may be space for metacognition to be introduced into school curricula, if the proposed "T-Levels" gain significant traction. Initially suggested by Lord Sainsbury (Boles 2016) the Technical Levels are intended to become vocational equivalents of A levels, which will have credibility with employers. Supported by Justine Greening (2017a), this could be an

opportunity for metacognition to be developed in the post-16 curriculum at least, perhaps alongside other twenty-first century skills discussed above. This would not address the teaching and learning of metacognition in Key Stage 1, 2, 3 or 4, but it might be a start.

Perhaps, though, rather than leave it to policy makers to dictate what constitutes an appropriately twenty-first century curriculum, teachers and school leaders should be the ones to take up the challenge of implementing “evidence-informed” practice and developing effective approaches to teaching metacognition across their classrooms. In terms of school leadership, it is now widely agreed that leadership has a significant impact on pupil outcomes. Leithwood et al. identify that “School leadership is second only to classroom teaching as an influence on pupil learning” (Leithwood, Harris, and Hopkins 2008, 27). This corroborates Hallinger and Heck’s cautious but firm conclusion that headteachers “exercise a measurable, though indirect effect on school effectiveness and student achievement.” (Hallinger and Heck 1998, 186). Regarding the roles of different leaders in schools, Day et al. (2009) assert the primacy of headteachers. Leithwood and Jantzi (2005) use a meta-analytical strategy in an attempt to isolate the impact of such leadership on children’s outcomes and conclude that the available evidence strongly suggests a positive link between leadership and children’s outcomes; a commonly quoted figure is that the headteacher typically accounts for between 5–7% of student learning (Braun, Gable, and Kite 2011; Leithwood, Harris, and Hopkins 2008). This theme is taken up and supported by the Organisation for Economic Cooperation and Development (OECD 2013) and McKinsey (McKinsey 2007), who both emphasise the significance of school leaders for improving student outcomes across the world. Some education systems, such as the evolving Welsh system, recognise the value of promoting metacognition in schools through leadership. The Welsh Leadership Standards (Wales 2016), state that a successful school leader, “Promotes and puts in place policies designed to enable learners to develop independence and to acquire thinking and learning skills.” Headteachers in Wales need to demonstrate that they do this in their schools; there is no such equivalent in England and metacognition is absent from the Teachers’ Standards (DfE 2011), as noted above.

In the context of Initial Teacher Education, while it is obviously important to ensure that beginning teachers have excellent subject knowledge, excellent behaviour management techniques and the like, it is also vitally important that they understand the centrality of metacognition. In fact there is little evidence about beginning teachers’ knowledge about metacognition (Zohar and Barzilai 2013). There is some research examining the effect of beginning teachers’ own sense of metacognition (Ozturk 2017); this suggests that where they have a relatively low sense of metacognition they are less likely to incorporate such strategies into their lessons, even when they have had detailed CPD about metacognition in the classroom, which is unsurprising. There is also strong, emerging evidence about the significance of teachers explicitly role modelling metacognition (Wall and Hall 2016) and how this can have a significantly positive impact on pupil learning. This should not come as a surprise, either, drawing as it does on the long tradition of scaffolding (Holton and Clarke 2006) and other socio-cognitive and socio-cultural (Bruner 1990) approaches to education, but it has perhaps been moved into the background of ITE and CPD.

Conclusion and recommendations

In this paper we have explored what the international literature suggests about the effects of teaching metacognition in schools. To do this we have also sought to answer four sub-questions:

Question 1: What does the international literature suggest about the effectiveness of metacognition on pupil outcomes in classrooms?

Question 2: What does the literature say about the relationship between metacognition and particular groups of pupils?

Question 3: What does the literature say about the relationship between metacognition and pupil wellbeing?

Question 4: What are the implications of what the international literature says about these questions for educational policy?

This review of the international literature indicates that there is a very positive relationship between teaching metacognition in schools and pupil outcomes, with a mean effect size of 0.65. This is a very significant effect size and is broadly consistent across all of the studies found through this systematic review of the literature. Some evidence indicates that teaching metacognition is very helpful for pupils from ethnic minorities, as well as for pupils who present challenging behaviours. There is limited, emerging, evidence indicating that pupils from low socio-economic groups can match, or even exceed, the academic performance of their peers from higher socio-economic groups when taught metacognitive strategies. There is limited evidence exploring the relationship between metacognition and pupil wellbeing, but there is substantial evidence that metacognition and motivation are intrinsically linked; thus it is reasonable to assume that success with metacognition will improve pupils' wellbeing and sense of agency.

The case of metacognition does raise interesting questions about the English government's attitude towards adopting "evidence-informed practice". Why, for example, has one pedagogical approach used in high-achieving school systems, such as "Shanghai Maths", been encouraged by the government, while metacognition, which is also used across high performing school systems, is not encouraged by the English government? There are also serious concerns about the reliance of Randomized Control Trials to inform education policy, which can result in a misleadingly "positivist" interpretation of data and, thus, poorly informed policy and practice.

Taking into account all of the evidence discussed above, then, it appears that there are potentially significant positive effects of schools developing the use of metacognition in a systematic way across the curriculum. It is apparent that pupils are more successful when a cross-curricular approach towards metacognition is taken across a school or a school system. Such an approach has implications for teacher CPD, the preparation and practice of school leaders and for Initial Teacher Education.

The next steps should include:

- The development of a whole school curriculum for metacognition, including the new T-levels
- The development of metacognitive awareness for school leaders
- The development of metacognition across ITE curricula, ITE institutions and early career developments

- The development of a “policy adoption” framework to help identify how a policy can be successful in a new context

There also needs to be greater research and development of tools which can be used to measure the impact of metacognition in classrooms. In fact, this should be a priority, as such a tool, which could be used with ease and clarity by teachers, would allow teachers to take ownership of the concept of metacognition and develop it further in their own contexts in a fully professional manner. Currently, the vast majority of interest in metacognitive approaches is located with academics. This means that the impact of metacognition in the classroom will be limited; it will only expand when teachers are “fluent” with metacognition, fully understand the benefits through their own experiences, and then have the autonomy and support to develop their own professional practice.

The available evidence strongly suggests that metacognitive approaches to teaching and learning have the potential to radically improve the outcomes and life chances of children, with some evidence suggesting that this is especially the case for disadvantaged children. Such knowledge then places a moral responsibility on policy makers to ensure that schools, school leaders and all those who support them, rapidly develop and implement practical strategies which can deliver, measure and improve metacognitive skills across all schools for all children.

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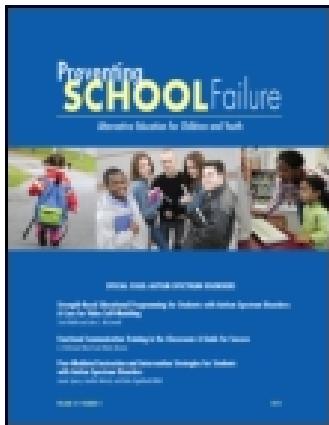
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Metacognition Needed: Teaching Middle and High School Students to Develop Strategic Learning Skills

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Metacognition Needed: Teaching Middle and High School Students to Develop Strategic Learning Skills

Nancy Joseph

ABSTRACT: Students' ineffective learning strategies are linked to poor metacognition, revealing that struggling learners have not developed the practical *figure it out* skills to succeed in academic challenges. Well-documented research has noted the positive effect of self-reflective learning on students' academic and personal development. Also, researchers have described that metacognitive awareness can be taught. The author explores these issues and presents practical suggestions that middle and high school teachers can use to help students develop metacognitive skills.

KEYWORDS: critical thinking, metacognition, middle and high school students, self-assessment

THE TEACHER EXPLAINS an assignment, presents examples, answers questions, and offers suggestions. Now it is time for independent classwork. Most of the students are busy reviewing the directions and starting the assignment; however, two students raise their hands to ask for assistance. The first student, moaning with frustration, complains to the teacher, "What are we supposed to do? This is confusing. I need help." The other student pauses for a minute and has a different response, "Oh, I just figured it out. I wasn't thinking about the list you gave us. I can do this."

Educators recognize that this situation is common in many middle and high school classrooms and acknowledge that a student's orientation to learning situations has a major effect on academic success. Some adolescents are confident and self-regulated learners who demonstrate introspective skills as they question their thinking and resolve confusions. By contrast, other students are passive and dependent learners who rely on the teacher or other students for assistance rather than on their own abilities to resolve difficulties.

When educators think about working with students, they ask themselves a few basic questions: "Why are some students successful with learning challenges, whereas others are easily frustrated?"; "How do students develop the ability to persevere with difficult tasks?" and, most importantly, "How can secondary teachers help students develop the

practical intelligence needed for academic success in their content-area classes?" These questions relate to students' metacognitive awareness—the ability to reflect on their own thinking and develop and use practical problem-solving skills to resolve learning difficulties. Some students have the cognitive skills to recognize when they are doing well and when they are going in the wrong direction. Working independently, these perceptive students use metacognition to plan, regulate, and assess their learning. However, many other students lack the practical intelligence and accompanying confidence that comes from well-developed thinking and learning skills, and their unfocused attempts cause confusion and frustration. Ineffective learning strategies are linked to poor metacognition, revealing that struggling students have not developed the practical *figure it out* skills to approach classroom challenges in a confident, independent manner (Hacker, Dunlosky, & Graesser, 1998; Williams et al., 2002). These students are unable to reflect on their thinking strategies; this inability is a deficiency that puts them far behind learners who are able to reflect on their thinking strategies. The purpose of this article is to explore students' cognitive abilities and to present practical suggestions that content-area teachers can use to help middle and high school students develop metacognitive awareness.

Research on Metacognition

Well-documented research studies in the past 3 decades have described the significance of metacognition, noting the positive effects of self-reflective learning on students' academic and personal development. Researchers have conveyed that metacognition is vital to the social learning

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theory and personality development, indicating that appropriately focused metacognitive instruction increases practical intelligence, thus enabling students to gain greater insights into their learning strategies (Flavell, 1979; Lambert, 2000). Successful students at all grade levels are self-regulated learners who assess their knowledge and examine their cognitive processes, abilities that become more important as students move from elementary to middle and high schools. Because skillful students are able to think about their own thinking, they can track their progress and reflect on their learning. However, many struggling students fail to understand the learning process and lack introspective skills, resulting in unproductive approaches to their schoolwork. Through metacognitive instruction, these students become aware of their own thinking and learn to work through challenges without undue frustration (Hoyt & Sorensen, 2001; Lifford, Byron, & Ziemian, 2000; Peverly, Brobst, & Morris, 2002).

Metacognitive awareness can be taught with research emphasizing classroom methods such as practicing techniques for introspective learning and talking about reading and thinking. Becoming a strategic learner through metacognitive awareness is a developmental and instructional process influenced by teachers' methods and materials (Jacobs, 2003; Paris & Paris, 2001). Educators recognize that students need to learn higher level thinking skills of metacognition because cognitive demands become more complex from one grade to the next. Instruction in metacognition at the elementary school level increases because research has indicated that even young students are able to monitor and assess their own learning. At the secondary school level, studies of adolescent learning have revealed that metacognitive awareness prompts students to develop practical thinking skills to use in their coursework and in life (Moje, 2002; Williams et al., 2002). Through the lifelong skill of metacognitive thinking, students can be taught to reflect on their own learning processes while they complete learning tasks. It is evident that metacognitive awareness creates self-regulated learning, allowing students to develop greater intellectual maturity.

Metacognition and Teaching

Most teachers have well-developed metacognitive skills because their roles require insightful, highly conscious cognitive activity and practical intelligence. Consider the thinking processes that educators use to assess planning and instruction. Metacognitive awareness allows teachers to reflect on their work, prompting them to evaluate their instructional goals, methods, and outcomes. For example, educators may ask themselves the following questions after teaching a vocabulary lesson: "What objectives did I have in mind?" "What was I thinking when I decided to focus on the vocabulary words prior to the reading activity?" "Did

the students understand my explanations?" "How could I make the information easier to understand?" and "Did I assess the students' learning appropriately?" These questions are typical of a teacher's mental processes, indicating that self-reflection is a natural part of teaching. However, a concern is that educators are not teaching students metacognitive awareness.

Educators recognize that students' metacognition may be overlooked in the classroom because most instruction focuses on the content rather than on the strategies used to learn the content. For many teachers—especially secondary school content teachers—thinking about the mental processes a novice learner needs to comprehend the subject-area material is not a natural activity (Schoenbach, Brauner, Greenleaf, & Litman, 2003). Another reason for neglecting metacognition is that instructional time is at a premium, with teachers responding to the pressures of state assessment testing and to the demands of local curriculum guidelines; therefore, the emphasis on learning strategies is limited. However, educators need to remember an essential question: What is more important than spending time teaching the critical thinking skills needed for independent learning? Encouraging students to practice reflective thinking does not add extra content; rather, it is a tool for mastering existing content. Many teachers have discovered that strategies for developing metacognitive skills can be embedded into traditional learning activities.

An important point to consider is that students' metacognition helps teachers understand student learning. Educators learn about themselves as teachers when they promote metacognitive awareness among their students because reflective thinking allows students to offer valuable feedback to their teachers regarding where their explanations were effective or confusing (i.e., students identify what they need as learners). The awareness of how students learn enables teachers to better focus the instruction and make better use of class time.

As educators know, some students are proficient and engaged learners who have developed metacognitive abilities on their own as they progressed from elementary to middle and high schools. With insightful knowledge about their learning styles, students independently recognize that they need to use a variety of problem-solving strategies to overcome learning challenges. However, most other students need focused instruction, practice, and encouragement to develop these abilities. Less proficient students miss the internal dialogue of metacognition, a deficiency that does not allow them to explore their thinking processes. For struggling adolescent learners, discussions about introspective thinking may cause confusion and anxiety because they have become comfortable with a passive and dependent approach to learning (Joseph, 2006). However, through guided instruction and practice over time, educators can

coach these students to develop effective learning strategies while breaking the habit of depending on others to resolve academic difficulties.

Classroom Practices

How can middle and high school teachers help students develop metacognitive awareness? Teachers can construct assignments that prompt students to practice new learning strategies in a supportive classroom environment, building their competence and confidence as learners (Vacca, 2002). Research has indicated that teachers should design lessons comprising three main components: direct instruction through teacher modeling, ongoing discussions about metacognition, and active classroom practice. In addition, teachers should use writing activities, such as reading logs and self-assessment checklists, to promote metacognitive growth because these exercises encourage students to reflect on their learning processes (Paris & Paris, 2001; Peverly et al., 2002). Educators should appropriately structure writing activities so that they are writing-to-learn activities, not just busy work. The following sections present classroom strategies for helping students develop metacognitive awareness.

Realistic Advice and Encouragement

Effective learning is based on good thinking and focused effort—a concept that many students do not understand because they believe that if they do not understand or “get it” the first time, the material is simply too hard for them to comprehend. This self-defeating attitude allows students to withdraw from learning situations. Some students lack confidence as learners, feeling that others are more skillful and smarter. Teachers should explain that successful learning develops through practice, concentration, and effort. All students benefit from thinking about their own thinking. Researchers have noted that less proficient learners make the greatest gains when metacognitive instruction is part of their classroom instruction, yet these students need the most support (Williams et al., 2002). To best assist struggling students, the following are recommendations for teachers:

1. Be aware of how students view themselves as learners and attempt to understand how they approach academic challenges.
2. Serve as a learning coach by working with students through each step of mastering new strategies for understanding their own thinking.
3. Encourage students to resolve their confusions and persevere with tasks, thus building their confidence as independent learners.

Thinking Strategies

Teachers should use mental modeling when working with students on reading assignments or problem-solving

activities. Using this think-aloud technique, teachers can demystify the reading process by explaining the behind-the-scenes thinking required for good comprehension. Teachers could select a passage from the textbook and ask students to follow along while reading aloud. During this process, teachers should offer comments on the thinking strategies they use to work through the material. Through mental modeling, teachers can demonstrate how a skillful learner approaches a task, providing insights that are unfamiliar to many learners. It is important to remind students that problem solving or reading a text is not always a simple process; students may encounter confusion, distractions, and frustration. However, teachers should emphasize that the students’ role as metacognitively aware learners is to find ways to resolve the challenges, explaining that students can be successful if they develop and apply a repertoire of comprehension strategies. Teachers have noted that pausing for explanations and teacher modeling brings positive results because the demonstration slows down the reading process and gives students time to reflect on their thinking, thus encouraging an understanding of independent learning strategies (Schoenbach et al., 2003).

Reciprocal-Teaching Activities

Reciprocal teaching helps students become comfortable with metacognitive thinking because it provides steps for exploring texts and encourages students to think about their comprehension strategies. Students can learn how to approach challenging texts through the step-by-step inquiry process of reciprocal teaching. Teachers should begin this structured activity by leading students through a think-aloud session to model four comprehension strategies of reciprocal teaching: generating questions based on the text, clarifying misunderstandings, summarizing, and predicting the content of the next section from the text. After showing the types of thinking needed for each strategy through the think-aloud activity, educators should ask students to work in groups to talk about the next passage in the text. Teachers should encourage students to move through the steps in the guided practice and to support each other as learners and thinkers. The goal is for the students to work independently through the steps of questioning, clarifying, summarizing, and predicting. With regular practice and careful monitoring, struggling readers can learn to apply the strategies of reciprocal teaching to their reading (Slater, 2002).

Discussions About Thinking

Teachers should use class time to discuss effective thinking techniques. Also, teachers should remind students that purposeful interaction with the text when reading means that they can hear the author’s voice in their minds. Good readers can demonstrate this skill to their peers by reading a passage aloud and explaining the thinking processes that

they use to comprehend the material as they “talk to the text.” Teachers may be surprised at what students say about their strategies. Teachers should provide opportunities for collaborative problem solving, encouraging students to discuss their approaches with their peers. Also, teachers should remember that metacognitive awareness may be second nature for successful learners, yet a new approach to learning for many other students. Spending class time to discuss metacognitive thinking strategies encourages students to understand themselves as learners.

Self-Assessment

Continuous student self-assessment—an important part of metacognitive awareness—encourages independent learning and prompts students to become more aware of their progress. Checklists, reading logs, and skills inventories are useful tools for self-assessment. For a self-assessment activity, teachers could select a few paragraphs from a class text and design a 5–10-min compare-and-contrast assignment. Teachers could instruct their students to read two paragraphs on different but related subjects and compare and contrast the material. After students complete the assignment, teachers could focus on the cognitive strategies they used to approach the content. Teachers should encourage them to reflect on their thinking behaviors by asking themselves a series of questions (see the Appendix).

Questioning

Through questioning, students can actively participate in their own learning and develop a wide range of cognitive processes. All students should be able to think, reflect, and question in an effective manner, yet questioning is often neglected because teachers feel the need to save time and move the lesson along at a pace that does not always allow much time for thinking and questioning. However, when students generate questions, their metacognitive skills develop because they must interpret, synthesize, analyze, and evaluate the material (Ciardiello, 1998; Penticoff, 2002). Students can demonstrate metacognitive awareness by reviewing their background knowledge before reading as they preview the material and by continuously asking themselves questions while reading. Teachers should use prereading activities to help students recognize the connections between their previous knowledge and new content.

Questioning is a powerful cognitive strategy because it prompts students to focus their learning by searching for the information they want to know, helping them focus and organize their thinking. Teachers should promote higher level thinking when introducing a new topic by requiring students to write five questions about the topic, beginning with the word *why*. Teachers should remember that asking students to generate questions does not follow the traditional teacher-student roles; therefore, some students may be

uncomfortable with this approach because they prefer to take a less active role by having the teacher pose the questions.

Problem-Solving Activities

Teachers should use problem-solving activities to promote active engagement with the content. These activities require students to shift from the basic recall of facts to an analysis and application of the content to a specific situation. When challenged by problem-solving assignments, students learn to recognize what they know and what they do not know, which is a major step toward metacognitive awareness. The following example of a problem-solving activity requires a variety of thinking tasks including reading, researching, discussing, and writing. This activity can be modified as needed for students in middle and high schools.

As a news reporter for *Science Today*, you are assigned to interview a scientist and write an article for the next issue of your magazine. Choose Madame Curie, Galileo, or Sir Isaac Newton. Spend some time reading about your scientist and discuss your ideas with your group. Your task consists of three parts: (a) Prepare 6–8 questions for the interview, (b) Write one page of notes about the scientist’s work and the time period in which he or she lived, and (c) Write a magazine article. The article should be 2–3 paragraphs and should focus on information that readers of *Science Today* would want to know about the scientist.

Conclusion

Educators recognize that integrating learning and thinking strategies into daily classroom activities on a long-term basis brings good results, helping students gain a better understanding of how successful learning takes place. Teaching students to monitor their cognitive processes by developing strategies for thinking, comprehending, and remembering is a valuable investment for their future. Through metacognitive instruction, students can practice these skills over time, increasing the chance that these valuable thinking strategies will strengthen their practical intelligence and become part of their repertoire as learners.

AUTHOR NOTE

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APPENDIX Self-Assessment Questions for Students

1. Did you understand the directions for the assignment?
2. What were you thinking when you worked on the assignment?
3. Did you feel confident? Confused? Frustrated?
4. How did you resolve any difficulties you experienced?
5. How would you evaluate your ability to concentrate on the assignment?

Metacognition: A Literature Review

Research Report

Emily R. Lai

April 2011

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Abstract

Metacognition is defined most simply as “thinking about thinking.” Metacognition consists of two components: knowledge and regulation. Metacognitive knowledge includes knowledge about oneself as a learner and the factors that might impact performance, knowledge about strategies, and knowledge about when and why to use strategies. Metacognitive regulation is the monitoring of one’s cognition and includes planning activities, awareness of comprehension and task performance, and evaluation of the efficacy of monitoring processes and strategies. Recent research suggests that young children are capable of rudimentary forms of metacognitive thought, particularly after the age of 3. Although individual developmental models vary, most postulate massive improvements in metacognition during the first 6 years of life. Metacognition also improves with appropriate instruction, with empirical evidence supporting the notion that students can be taught to reflect on their own thinking. Assessment of metacognition is challenging for a number of reasons: (a) metacognition is a complex construct; (b) it is not directly observable; (c) it may be confounded with both verbal ability and working memory capacity; and (d) existing measures tend to be narrow in focus and decontextualized from in-school learning. Recommendations for teaching and assessing metacognition are made.

Keywords: metacognition, self-regulated learning

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Metacognition: A literature review

Educational psychologists have long promoted the importance of metacognition for regulating and supporting student learning. More recently, the Partnership for 21st Century Skills has identified self-directed learning as one of the life and career skills necessary to prepare students for post-secondary education and the workforce. However, educators may not be familiar with methods for teaching and assessing metacognition, particularly among elementary-aged children. The purpose of this literature review is fourfold: (1) to explore the ways in which metacognition has been defined by researchers; (2) to investigate how metacognition develops in young children; (3) to learn how teachers can encourage development of metacognitive skills in their students; and (4) to review best practices in assessing metacognition.

Definition of Metacognition

John Flavell originally coined the term metacognition in the late 1970s to mean “cognition about cognitive phenomena,” or more simply “thinking about thinking” (Flavell, 1979, p. 906). Subsequent development and use of the term have remained relatively faithful to this original meaning. For example, researchers working in the field of cognitive psychology have offered the following definitions:

- “The knowledge and control children have over their own thinking and learning activities” (Cross & Paris, 1988, p. 131)
- “Awareness of one’s own thinking, awareness of the content of one’s conceptions, an active monitoring of one’s cognitive processes, an attempt to regulate one’s cognitive processes in relationship to further learning, and an

application of a set of heuristics as an effective device for helping people organize their methods of attack on problems in general” (Hennessey, 1999, p. 3)

- “Awareness and management of one’s own thought” (Kuhn & Dean, 2004, p. 270)
- “The monitoring and control of thought” (Martinez, 2006, p. 696)

As Kuhn and Dean (2004) explain, metacognition is what enables a student who has been taught a particular strategy in a particular problem context to retrieve and deploy that strategy in a similar but new context. The authors note that in cognitive psychology, metacognition is often defined as a form of executive control involving monitoring and self-regulation, a point echoed by other researchers (McLeod, 1997; Schneider & Lockl, 2002). Further, Schraw (1998) describes metacognition as a multidimensional set of general, rather than domain-specific, skills. These skills are empirically distinct from general intelligence, and may even help to compensate for deficits in general intelligence and/or prior knowledge on a subject during problem solving.

Constituent Elements of Metacognition

Metacognition has two constituent parts: knowledge about cognition and monitoring of cognition (Cross & Paris, 1988; Flavell, 1979; Paris & Winograd, 1990; Schraw & Moshman, 1995; Schraw et al., 2006; Whitebread et al., 1990). Several frameworks have been developed for categorizing types of knowledge about cognition. Table 1 organizes components from each of these frameworks to facilitate comparisons among them. For example, Flavell (1979) defines cognitive knowledge as knowledge about one’s own cognitive strengths and limitations, including the factors (both internal and external) that may interact to affect cognition. He classifies such knowledge into three types: (1) “person” knowledge, which includes anything one

believes about the nature of human beings as cognitive processors; (2) “task” knowledge, which includes knowledge about the demands of different tasks; and (3) “strategy” knowledge, which is knowledge about the types of strategies likely to be most useful. Flavell notes that these different types of knowledge can interact, as in the belief that one should use strategy A (versus strategy B) to solve task X (rather than task Y).

Table 1

Typology of Metacognitive Components

Metacognitive Component	Type	Terminology	Citation
Cognitive knowledge	Knowledge about oneself as a learner and factors affecting cognition	Person and task knowledge	Flavell, 1979
		Self-appraisal	Paris & Winograd, 1990
		Epistemological understanding	Kuhn & Dean, 2004
		Declarative knowledge	Cross & Paris, 1988 Schraw et al., 2006
	Awareness and management of cognition, including knowledge about strategies	Procedural knowledge	Cross & Paris, 1988 Kuhn & Dean, 2004 Schraw et al., 2006
		Strategy knowledge	Flavell, 1979
		Conditional knowledge	Schraw et al., 2006
	Knowledge about why and when to use a given strategy	Planning	Cross & Paris, 1988 Paris & Winograd, 1990 Schraw et al., 2006
			Schraw & Moshman, 1995 Whitebread et al., 2009
Cognitive regulation	Attending to and being aware of comprehension and task performance	Monitoring or regulating	Cross & Paris, 1988 Paris & Winograd, 1990 Schraw et al., 2006
			Schraw & Moshman, 1995 Whitebread et al., 2009
	Assessing the processes and products of one's learning, and revisiting and revising learning goals	Cognitive experiences	Flavell, 1979
		Evaluating	Cross & Paris, 1988 Paris & Winograd, 1990 Schraw et al., 2006
			Schraw & Moshman, 1995 Whitebread et al., 2009

Subsequent metacognition researchers have offered a slightly different framework for categorizing cognitive knowledge. For example, several researchers have used the concepts of declarative and procedural knowledge to distinguish cognitive knowledge types (Cross & Paris, 1988; Kuhn, 2000; Schraw et al., 2006; Schraw & Moshman, 1995). Kuhn and Dean (2004) characterize declarative cognitive knowledge broadly as epistemological understanding, or the student's understanding of thinking and knowing in general. Schraw et al. (2006) portray declarative cognitive knowledge as knowledge about oneself as a learner and what factors might influence one's performance. Paris and Winograd (1990) discuss the process of self-appraisal as reflection about personal knowledge states to answer the question, "Do I know this?" Finally, Cross and Paris (1988) define declarative cognitive knowledge specifically within the context of reading as awareness of the factors that might affect reading ability.

On the other hand, procedural knowledge involves awareness and management of cognition, including knowledge about strategies (Cross & Paris, 1988; Kuhn & Dean, 2004; Schraw et al., 2006). Schraw et al. (2006) also distinguish conditional cognitive knowledge, which is knowledge of why and when to use a given strategy. The authors point out that cognitive knowledge is "late developing," in the sense that children often exhibit deficits in cognitive knowledge. In addition, although the ability to explicitly articulate cognitive knowledge tends to improve with age, many adults struggle to explain what they know about their thinking. This latter result suggests that cognitive knowledge may not need to be explicit in order for people to access and use it.

The other component of metacognition is monitoring of one's cognition, which many researchers have argued includes activities of planning, monitoring or regulating, and evaluating (Cross & Paris, 1988; Paris & Winograd, 1990; Schraw & Moshman, 1995; Schraw et al., 2006;

Whitebread et al., 2009). Planning involves identification and selection of appropriate strategies and allocation of resources, and can include goal setting, activating background knowledge, and budgeting time. Monitoring or regulating involves attending to and being aware of comprehension and task performance and can include self-testing. Finally, evaluation is defined as “appraising the products and regulatory processes of one’s learning,” and includes revisiting and revising one’s goals (Schraw et al., 2006, p. 114).

Flavell (1979) discusses cognitive monitoring in the context of “cognitive experiences,” which are insights or perceptions that one experiences during cognition, such as, “I’m not understanding this.” Flavell notes that these experiences serve as “quality control” checks that help learners revise their goals. Haller et al. (1988) identify three clusters of mental activity inherent in metacognition within the context of reading comprehension, including awareness, monitoring, and regulating. According to this framework, awareness entails recognition of explicit and implicit information and responsiveness to text dissonance or inaccuracies. Monitoring involves goal setting, self-questioning, paraphrasing, activating relevant background knowledge, making connections between new and previously learned content, and summarizing to enhance comprehension during reading. Finally, regulating refers to “compensatory strategies to redirect and bolster faltering comprehension” (p. 6).

Researchers have observed a relationship between cognitive knowledge and cognitive monitoring. For example, Flavell (1979) argues that metacognitive experiences that allow one to monitor and regulate one’s cognition play a major role in the development and refinement of metacognitive knowledge. In turn, Schraw (1998) cites a number of empirical studies demonstrating that cognitive knowledge appears to facilitate cognitive regulation. He notes that such studies have found cognitive knowledge and cognitive regulation to be correlated with one

another at about $r = .50$, which suggests that around one-quarter of the variance in cognitive knowledge is attributable to cognitive regulation and vice versa. Further, Schraw and Moshman (1995) argue that cognitive knowledge and cognitive regulation are integrated in metacognitive theories. There are three types of such theories, which individuals construct in order to systematize cognitive knowledge and plan cognitive activities. Tacit theories are constructed without explicit awareness from personal experiences or interactions with peers. These theories may be difficult to change precisely because they are implicit. Informal theories are characterized as “fragmentary”; in other words, individuals may be aware of some aspects of these theories, but lack an explicit structure for organizing their beliefs about knowledge. Over time, these informal theories are expected to become more sophisticated and formalized. Finally, formal theories are highly systematized and structured. These theories are rare, and because they are explicit, more subject to “purposeful and rigorous evaluation” (Schraw & Moshman, 1995, p. 362).

Relationship to Other Concepts

Researchers in cognitive psychology have linked metacognition to a number of other constructs, including metamemory, critical thinking, and motivation. For example, metamemory is closely related to metacognition, particularly cognitive knowledge. Metamemory is “knowledge about memory processes and contents,” and consists of two components that closely mirror the declarative and procedural aspects of cognitive knowledge (Schneider & Lockl, 2002, p. 5). Variables, which correspond to declarative knowledge, refer to “explicit, conscious, factual knowledge that performance in a memory task is influenced by a number of different factors or variables” (p. 6). Sensitivity, which corresponds to procedural knowledge, is knowledge about when a particular memory strategy might be useful. According to Schneider and Lockl (2002),

most developmental studies of metacognition have actually focused on the construct of metamemory, particularly its procedural dimension.

Critical thinking also relates to metacognition. Definitions of critical thinking vary widely, but common elements of most definitions include the following component skills:

- analyzing arguments (Ennis, 1985; Facione, 1990; Halpern, 1998; Paul, 1992);
- making inferences using inductive or deductive reasoning (Ennis, 1985; Willingham, 2007; Paul, 1992; Facione, 1990);
- judging or evaluating (Case, 2005; Ennis, 1985, Facione, 1990; Lipman, 1988; Tindal & Nolet, 1995);
- making decisions or solving problems (Ennis, 1985; Halpern, 1998; Willingham, 2007).

In addition to skills or abilities, critical thinking also entails dispositions. These dispositions, which can be seen as attitudes or habits of mind, include open- and fair-mindedness, inquisitiveness, flexibility, a propensity to seek reason, a desire to be well-informed, and a respect for and willingness to entertain diverse viewpoints (Bailin et al., 1999; Ennis, 1985; Facione, 1990; Halpern, 1998; Paul, 1992). Finally, there appear to be both general and domain-specific aspects of critical thinking, which suggests that instruction should represent a fusion of preparation in general critical thinking principles, as well as practice in applying critical thinking skills within the context of specific domains (Ennis, 1989; Facione, 1990; Paul, 1992).

Flavell (1979) and Martinez (2006) maintain that critical thinking is subsumed under metacognition. For example, Flavell argues that the definition of metacognition should include

critical thinking when he argues that “critical appraisal of message source, quality of appeal, and probable consequences needed to cope with these inputs sensibly” can lead to “wise and thoughtful life decisions” (p. 910). Martinez defines critical thinking as “evaluating ideas for their quality, especially judging whether or not they make sense,” and sees it as one of three types of metacognition, along with metamemory and problem solving (p. 697). Kuhn (1999) equates critical thinking with metacognition. Similarly, Hennessey (1999) identifies a list of metacognitive skills that are quite similar to skills commonly included in definitions of critical thinking:

- considering the basis of one’s beliefs;
- temporarily bracketing one’s conceptions in order to assess competing conceptions;
- considering the relationship between one’s conceptions and any evidence that might or might not support those conceptions;
- considering explicitly the status of one’s own conceptions;
- evaluating the consistency and generalizability inherent in one’s conceptions.

Schraw et al., however, see both metacognition and critical thinking as being subsumed under self-regulated learning, which they define as “our ability to understand and control our learning environments” (p. 111). Self-regulated learning entails metacognition, motivation, and cognition, which includes critical thinking (2006). At the very least, metacognition can be seen as a supporting condition for critical thinking, to the extent that monitoring the quality of one’s thought makes it more likely that one will engage in high-quality (critical) thinking.

Finally, several researchers highlight the link between metacognition and motivation (Cross & Paris, 1988; Eisenberg, 2010; Martinez, 2006; Paris & Winograd, 1990; Ray & Smith, 2010; Schraw et al., 2006; Whitebread et al., 2009). Paraphrasing Gredler, Broussard and Garrison define motivation as “the attribute that moves us to do or not to do something” (2004, p. 106). Gottfried defines academic motivation in particular as the “enjoyment of school learning characterized by a mastery orientation; curiosity; persistence; task-endogeneity; and the learning of challenging, difficult, and novel tasks” (1990, p. 525). In the context of metacognition, motivation is defined as “beliefs and attitudes that affect the use and development of cognitive and metacognitive skills” (Schraw et al., 2006, p. 112). According to Schraw et al. (2006) motivation has two primary subcomponents: (1) self-efficacy, which is confidence in one’s ability to perform a specific task and (2) epistemological beliefs, which are beliefs about the origin and nature of knowledge. Cross and Paris (1988) note that metacognition includes affective and motivational states. Similarly, Martinez (2006) argues that metacognition entails the management of affective states, and that metacognitive strategies can improve persistence and motivation in the face of challenging tasks. Paris and Winograd (1990) concur, arguing that affect is an inevitable element of metacognition, because as students monitor and appraise their own cognition, they will become more aware of strengths and weaknesses.

Eisenberg (2010) reviews the research on young children’s emotion-related self-regulation, which is the set of “processes used to manage and change if, when, and how one experiences emotions and emotion-related motivation and physiological states and how emotions are expressed behaviorally” (p. 681). This emotion-related self-regulation refers to monitoring and regulating the impact of emotions and motivational states on one’s performance and parallels the regulation of cognition involved in the executive functioning dimension of metacognition.

Eisenberg defines one subskill, known as effortful control (EC), as “the efficiency of executive attention—including the ability to inhibit a dominant response and/or activate a subdominant response, to plan, and to detect errors” (p. 682). Eisenberg argues that EC is indirectly related to academic success through motivation. Eisenberg explains the relationship as follows: children high in EC are more likely to behave in productive, pro-social ways; they are more socially competent and are generally rated as having higher quality interactions with others. Such pro-social children are more likely to engage in school to the extent that they feel socially comfortable. This increased motivation is then hypothesized to lead to higher achievement. Eisenberg concludes that the extant empirical research tends to support this proposed link, suggesting that interventions designed to improve students’ EC may lead to better peer interactions, higher engagement with schoolwork, and improved learning outcomes. For example, preschoolers’ EC predicted future SAT scores and also correlated with interpersonal skills and motivation. Ray and Smith (2010) echo this conclusion, arguing that EC predicts kindergarten students’ future reading and math abilities.

Development of Metacognition

This section reviews the empirical literature on the metacognitive capacities of preK and elementary-aged children, followed by an investigation of how metacognitive capacities appear, develop, and improve over time with age.

Empirical Evidence on the Metacognitive Skills of Young Children

Research in the Piagetian tradition has been quite influential in shaping expectations of young children’s metacognitive capacity (McLeod, 1997). Researchers studying Piaget’s work have often concluded that young children are not capable of formal operations, which are

necessary for abstract thought. Accordingly, as noted by several researchers, early studies on the metacognitive capacities of young children tended to conclude, rather pessimistically, that metacognition is a late-developing skill (Flavell, 1979; Schraw & Moshman, 1995; Whitebread et al., 2009). Indeed, accepted wisdom held that children typically do not develop metacognitive skills before 8-10 years of age (Whitebread et al., 2009). Summarizing the results of early studies in metamemory, Flavell (1979) argues that young children have difficulty appraising their own ability to memorize a set of objects and identifying what they do and do not understand about a set of written instructions. Schraw and Moshman (1995) note that young children have difficulty monitoring their thinking during task performance and constructing metacognitive theories—frameworks that integrate cognitive knowledge and cognitive regulation. Planning also appears to be a late-developing skill, with dramatic improvements in the ability to select appropriate strategies and allocate resources not appearing until 10-14 years of age.

However, more recent empirical work has cast doubt on the conclusions of earlier studies. For example, Schraw and Moshman (1995) observe that, although cognitive knowledge tends to improve with age, by the age of 4, children are able to theorize about their own thinking at a very simple level and appear to use simple theories to regulate their learning. Similarly, Whitebread et al. (2009) found that children as young as 3-5 years old exhibited both verbal and nonverbal metacognitive behaviors during problem solving, including articulation of cognitive knowledge, cognitive regulation, and regulation of emotional and affective states. McLeod (1997) points out that researchers have observed metacognition even in preschool-aged children, in the form of planning and monitoring progress toward goals and persistence at challenging tasks. Moreover, children as young as 6 can reflect with accuracy on their cognition (Schraw &

Moshman, 1995), and Hennessey (1999) observed first-grade students evaluating the plausibility of their science conceptions.

Schneider (2008) followed 174 children from the ages of 3 to 5, investigating the relationship between theory of mind at age 3 and subsequent development of metamemory. Theory of mind (ToM) refers to the “ability to estimate mental states, such as beliefs, desires, or intentions, and to predict other people’s performance based on judgments of their mental states” (p. 115). Schneider also examined the role of language ability in the development of metamemory. He found that both ToM and language ability increased steadily with age. Further, there was a strong relationship between language ability and both ToM and metamemory. Strong language ability at age 3 was a salient predictor of metamemory at age 5. Schneider hypothesizes that ToM facilitates the acquisition of metacognitive knowledge and vocabulary in young children, arguing that “early ToM competencies can be considered as a precursor of subsequent metamemory” (p. 116). Although results suggest that declarative metacognitive knowledge tends to increase with age, developmental trends for procedural metacognitive knowledge, particularly as it relates to monitoring task demands in relation to abilities, were less clear.

Young children’s ToM abilities may, in turn, depend on their capacity for executive functioning. To the extent that metacognition entails planning, self-regulation of both cognition and affective or motivational states, and allocation of attention and other intellectual resources, executive functioning forms part of the construct. Investigating the relationship between inhibitory control and ToM in preschool children, Carlson and Moses (2001) argue that executive functioning may be a prerequisite skill for the development of metacognition. Inhibitory control (IC) is “the ability to inhibit responses to irrelevant stimuli while pursuing a cognitively represented goal” (p. 1033). Studies investigating children’s IC have typically used

measures such as a child's ability to delay gratification or to suppress dominant impulses to respond to tasks in certain preprogrammed ways when instructed to do so. Empirical research suggests that significant development of IC abilities occurs during the first 6 years of life, with noticeable improvements occurring between the ages of 3 and 6. This development parallels maturation of the brain, particularly areas responsible for executive functioning. Carlson and Moses investigated the relationship between IC and ToM in 107 students from the ages of 3 to 4. They found ToM ability to significantly improve with age. Further, IC and ToM were significantly related, even after controlling for age, gender, and verbal ability. The authors speculate, and found some evidence to support, the possibility that both IC and working memory capacity mediate the relationship between general executive functioning and ToM.

Development of Metacognition Over Time

Kuhn (2000) characterizes development of metacognition as the very gradual (and not always unidirectional) movement to acquire better cognitive strategies to replace inefficient ones. Several researchers have concluded that metacognitive abilities appear to improve with age (Cross & Paris, 1988; Hennessey, 1999; Kuhn & Dean, 2004; Schneider, 2008; Schneider & Lockl, 2002; Schraw & Moshman, 1995). Schraw and Moshman (1995) posit that metacognitive development proceeds as follows: cognitive knowledge appears first, with children as young as age 6 able to reflect on the accuracy of their cognition, and consolidation of these skills typically evident by 8-10 years of age. Ability to regulate cognition appears next, with dramatic improvements in monitoring and regulation appearing by 10-14 years of age in the form of planning. Monitoring and evaluation of cognition are slower to develop and may remain incomplete in many adults. Finally, the construction of metacognitive theories appears last (if at all). These theories allow for the integration of cognitive knowledge and cognitive regulation.

Children spontaneously construct these theories as they come to reflect on their own thinking and learning. Metacognitive theories tend to originate within a particular domain, and to gradually extend to other domains. These theories begin as implicit and informal, becoming more systematized and formalized over time.

Kuhn and Dean (2004) portray epistemological understanding as a benchmark in the development of metacognition. According to this developmental framework, preschool children are realists, who equate believing with knowing. In other words, young children believe that everyone perceives the same thing, and all perceptions match external reality. By around age 4, however, children learn that some beliefs can be wrong. At this stage, called absolutism, children learn that two people's beliefs can differ, but only because one person is right and the other is wrong. By adolescence, most people recognize that even experts can disagree on certain topics. At this point, many descend into multiplism (or complete relativism), where everything is subjective, no beliefs can be judged, and all opinions are equally right. By adulthood, many people will have learned to tolerate some uncertainty, while still maintaining that there can be better or worse opinions to the extent that they are supported with reason and evidence (evaluative epistemology). Kuhn and Dean argue that there is very little that needs to be done to encourage children to progress through the first three stages; rather, it is progression to the fourth stage that requires some instructional effort.

Finally, Schneider and Lockl (2002) link development of metacognition with development of declarative metamemory, first evidenced by a child's understanding of mental verbs such as "know," "think," "remember," and "forget." Preschoolers and kindergartners appear to have a limited understanding of memory, but they seem to understand the terms. From the age of 4 years on, memory verbs can be correctly applied to describe mental states. Between

the ages of 6 and 11, there appear to be large gains in procedural metamemory knowledge. Prior to this time, children tend to over-estimate their memory performance, believing that performance is linked more strongly to effort than it actually is. By the age of 9 or 10, most children realize that task characteristics and use of strategies can make remembering more or less difficult, and students by the age of 12 can make more subtle distinctions in the differential effectiveness of various memory strategies. By this time, students are also able to self-regulate efficiently, in terms of allocating study time and attention. Development of strategic knowledge continues through adolescence and young adulthood, when students learn about interactions between memory variables, such as task characteristics, strategies, and effort.

There is at least some evidence, however, that general metacognition does not necessarily increase with age. Sperling et al. (2002) developed and administered a self-report instrument for measuring general metacognitive knowledge and regulation in children in grades 3-8. Empirical results validated the instrument's multidimensional approach to conceptualizing metacognition. In addition, the measure was significantly related to other, published measures of metacognition and only weakly correlated with measures of achievement. However, researchers found that mean scores on these instruments either decreased or stayed the same across grade levels. Thus, there was a slight tendency for younger students to earn higher metacognition scores than older students. The researchers speculated that because the instrument measures general metacognition rather than metacognition in the context of a specific subject, perhaps metacognition becomes more domain-specific as students age and acquire more specialized content knowledge. The study provided at least some support for this speculation, as correlations between scores on the self-report instrument and teachers' ratings of students' metacognition appeared to be weaker for older students (whose ratings were completed by teachers responsible for a single subject area)

than they were for younger students (whose ratings were completed by teachers responsible for multiple subject areas). In addition, the relationship between general metacognition and achievement in reading and math was weaker for older students than it was for younger students. Thus, it is possible that metacognition is domain-general among younger students, but gradually becomes more domain-specific for older students.

Instructional Implications

This section reviews the empirical evidence on the “teachability” of metacognitive skills, followed by a summary of specific instructional recommendations for fostering the development of metacognition.

Empirical Evidence on Teaching Metacognition

Several researchers offer evidence that metacognition is teachable (Cross & Paris, 1988; Dignath et al., 2008; Haller et al., 1988; Hennessey, 1999; Kramarski & Mevarech, 2003). For example, Cross and Paris (1988) describe an intervention targeted at improving the metacognitive skills and reading comprehension of 171 students in third and fifth grades. Children were exposed to a curriculum (Informed Strategies for Learning) designed to increase their awareness and use of effective reading strategies. During instruction, students received strategy training that included explicit attention to declarative, procedural, and conditional knowledge about reading strategies. Students in both grades made significant gains relative to comparison students with regard to awareness about reading in three areas—evaluation of task difficulty and one’s own abilities, planning to reach a goal, and monitoring progress towards the goal.

Dignath et al. (2008) meta-analyzed 48 studies investigating the effect of training in self-regulation on learning and use of strategies among students in first through sixth grades. Table 2 reports selected effect sizes for the various types of interventions.

Table 2

Summary of Selected Results from Dignath et al., 2008

Type of Treatment	Mean Effect Size
Any self-regulation training (metacognitive, cognitive, and motivational)	0.73
Metacognitive and motivational strategies training (all strategies)	0.97
Metacognitive and cognitive strategies training (all strategies)	0.81
Metacognitive strategies training (all strategies)	0.54
Metacognitive strategy training in planning and monitoring	1.50
Metacognitive strategy training in planning and evaluation	1.46
Training on metacognitive reflection – knowledge about and value of strategies	0.95
Cognitive strategies training (all strategies)	0.58
Cognitive strategy training in elaboration	1.19
Cognitive strategy training in elaboration, organization, problem solving	0.94
Cognitive strategy training in problem solving	0.72

The overall effect size for all studies examining the effect of any type of self-regulation training on the use of cognitive or metacognitive strategies was 0.73. Training that specifically emphasized metacognitive strategies had an effect size of 0.54. Training approaches that combined metacognitive components with other aspects of self-regulation, such as cognitive or motivational strategies, were even more successful, with average effect sizes of 0.81 and 0.97, respectively. The most successful cognitive strategies included elaboration taught in isolation (mean effect size = 1.19), followed by a combination of elaboration, organization, and problem

solving strategies (mean effect size = 0.94) and problem solving taught in isolation (mean effect size = 0.72). The most effective metacognitive strategies included the combination of planning and monitoring (mean effect size = 1.50) and the combination of planning and evaluation (mean effect size = 1.46), both of which were more successful than teaching any of the skills in isolation or teaching a combination of all three metacognitive skills (planning, monitoring, and evaluation). In studies where the intervention also included instruction designed to promote student metacognitive reflection, the most effective type of instruction emphasized a combination of knowledge about strategies as well as specific benefits of those strategies (mean effect size = 0.95).

Haller et al. (1988) meta-analyzed 20 empirical studies, comprising more than 1,500 students, on the effects of metacognitive instruction on students' metacognition during reading. They computed a mean effect size of 0.71, which suggests that instruction in metacognition can have robust effects on children's reading awareness and comprehension. Effects were largest for students in the seventh and eighth grades, but were also impressive among students in the second and third grades. The most modest effect sizes were found among students in fourth through sixth grades. Results suggest that instructional interventions involving fewer than 10 minutes of instruction per lesson are insufficient for producing these types of effects. The most effective instructional strategies included the textual-dissonance approach, self-questioning, and backward-forward search strategies, although the authors recommend using a variety of diverse techniques for best results.

Hennessey (1999) describes an instructional program involving 170 students in grades 1 through 6 over a period of three years. Students engaged in science units designed to explore students' science conceptions and the nature of science, with activities focusing specifically on

development of metacognition. Teachers' instruction emphasized making students' science conceptions visible, creating opportunities for students to clarify their conceptions in small groups, promoting metacognitive discourse among students, encouraging conceptual conflict, and facilitating student practice in different contexts. Hennessey concludes that students did exhibit qualitative changes in their metacognitive abilities from one year to the next, with students as young as first graders exhibiting the highest level of metacognition.

Finally, Kramarski and Mevarech (2003) report the results of a study investigating the effects of metacognitive training on the mathematical reasoning and metacognitive skills of 384 eighth-grade students. They found that students exposed to metacognitive instruction in either cooperative or individualized learning environments outperformed comparison students with respect to the ability to interpret graphs, fluency and flexibility of correct mathematical explanations, use of logical arguments to support math reasoning, performance on transfer tasks, and level of domain-specific metacognitive knowledge, such as strategies for representing math concepts in multiple ways and specific mathematical strategies for interpreting graphs.

Specific Instructional Strategies

Researchers have recommended a number of specific instructional approaches to teaching metacognition. For example, many researchers have noted the importance of providing explicit instruction in both cognitive knowledge and cognitive regulation. Cross and Paris (1988) recommend providing explicit instruction in declarative, procedural, and conditional knowledge. Similarly, Schraw et al. (2006) and Schraw (1998) urge educators to provide explicit instruction in cognitive and metacognitive strategies. Further, Schraw emphasizes that such strategy training needs to emphasize how to use strategies, when to use them, and why they are beneficial. A

number of other researchers echo the importance of highlighting the value of particular strategies in order to motivate students to use them strategically and independently (Cross & Paris, 1988; Kramarski & Mevarech, 2003; Schneider & Lockl, 2002).

In addition to providing instruction on cognitive knowledge, educators should also assist students in developing their abilities to monitor and regulate their cognition. Most of these recommendations concern the level of teacher scaffolding and structure provided. For example, Kuhn (2000) points out that instruction for metacognition should be delivered at the meta-level rather than the performance level, which means instruction should be aimed at increasing awareness and control of meta-task, rather than task, procedures. Schraw (1998) recommends providing explicit prompts to help students improve their regulating abilities. He suggests using a checklist with entries for planning, monitoring, and evaluation, with subquestions included under each entry that need to be addressed during the course of instruction. Such a checklist, he argues, helps students to be more systematic and strategic during problem solving. Similarly, Kramarski and Mevarech (2003) provided students with sets of metacognitive questions, including comprehension questions, strategic questions, and connection questions, to be completed during the task. Comprehension questions were designed to encourage students to reflect on a problem before solving it. Strategic questions were designed to encourage students to think about what strategy might be appropriate for a given task and to provide a reason or rationale for that strategy choice. Finally, connection questions were designed to encourage students to identify and recognize deep-structure task attributes so that they could activate relevant strategy and background knowledge.

Researchers also recommend the use of collaborative or cooperative learning structures for encouraging development of metacognitive skills (Cross & Paris, 1988; Hennessey, 1999;

Kramarski & Mevarech, 2003; Kuhn & Dean, 2004; Martinez, 2006; McLeod, 1997; Paris & Winograd, 1990; Schraw & Moshman, 1995; Schraw et al., 2006). This recommendation appears to be rooted in Piagetian and Vygotskyian traditions that emphasize the value of social interactions for promoting cognitive development (as summarized in Dillenbourg et al., 1996). Piaget touted the instructional value of cognitive conflict for catalyzing growth, typically achieved by interacting with another person at a higher developmental stage. Along similar lines, Vygotsky identified the zone of proximal development as the distance between what an individual can accomplish alone and what he/she can accomplish with the help of a more capable other (either a peer or adult). Each of these approaches highlights the potential for cognitive improvement when students interact with one another.

Proponents of collaborative learning approaches include Cross and Paris (1988), who identify group discussions about the use of reading strategies as one of the critical features of the Informed Strategies for Learning curriculum. Hennessey (1999) points out that such techniques promote metacognitive discourse among students and stimulate conceptual conflict. Such conflict can lead to clarifications of students' beliefs and concepts. Similarly, Kramarski and Mevarech (2003) attribute the superior performance of students working in collaborative group settings to the higher quality of discourse observed among students working together. Students participating in cooperative learning expressed their mathematical ideas in writing more ably than did those who worked alone. Moreover, as Schraw and Moshman (1995) note, peer interaction can encourage the construction and refinement of metacognitive theories, which are frameworks for integrating cognitive knowledge and cognitive regulation. Kuhn and Dean (2004) argue that social discourse can cause students to "internalize" processes of providing elaborations and explanations, which have been associated with improved learning outcomes.

Schraw et al. (2006) point out that small group work should involve peers at a similar developmental level, because they can provide examples within the learner's zone of proximal development. Further, they observe that collaborative learning works especially well when students have been explicitly taught how to collaborate, a point echoed by Kramarski and Mevarech (2003).

Other instructional recommendations include making student reasoning, concepts, and beliefs visible (Hennessey, 1999) by having students construct conceptual or mental models of the phenomena under study. Construction of such models may facilitate conceptual change for students holding inappropriate science conceptions, particularly if the process of developing and refining such models produces cognitive disequilibrium or conflict (Schraw et al., 2006).

Teachers are also urged to promote general awareness of metacognition by modeling metacognitive skills during instruction, perhaps by "thinking aloud" (Kramarski & Mevarech, 2003; Martinez, 2006; Schraw, 1998). Educators should not neglect the affective and motivational aspects of metacognition, including self-efficacy, learning attributions, and goal orientations (Schraw, 1998). According to Schraw, students may possess the requisite knowledge and skills, but fail to use them. "In general, successful students have a greater sense of self-efficacy, attribute their success to controllable factors such as effort and strategy use, and persevere when faced with challenging circumstances" (p. 122).

Assessment Implications

This section reviews challenges in assessing metacognition, describes extant methods of assessing or measuring metacognition, and identifies specific recommendations from the literature for measuring metacognition.

Challenges in Assessing Metacognition

Researchers have noted challenges in assessing metacognition. For example, metacognition is not directly observable in students (Sperling et al., 2002). First, Whitebread et al. (2009) argue that self-report methods, such as the use of rating scales or questionnaires that ask respondents to describe their use of particular strategies, rely too heavily on verbal ability. In addition, techniques that ask respondents to “think aloud” while engaging in a task do not capture implicit cognitive processes. In other words, subjects may not be aware of their cognitive knowledge and monitoring, which suggests that think-aloud methods may underestimate an individual’s metacognitive capacity. Moreover, these problems are compounded in preschool- and elementary-aged children, whose verbal ability and working memory capacities are incompletely developed. Thus, self-report and think-aloud techniques may be especially likely to underestimate the metacognitive abilities of young children. Finally, metacognition is a complex construct, involving cognitive knowledge and cognitive regulation. Moreover, there are multiple types of cognitive knowledge (declarative, procedural, conditional) as well as different types of cognitive regulation (planning, monitoring or regulating, and evaluating). Metacognition also entails affective and motivational states, including concepts such as effortful control and inhibitory control. Schraw and Moshman (1995) note that such complexity makes unreliability an issue.

Extant Assessment Methods

Given the complexity of the construct, many researchers have chosen to focus on only one or a few aspects of metacognition. Thus, measurement and assessment instruments designed to capture metacognition have typically focused somewhat narrowly on only a single dimension

of the construct. Furthermore, because metacognition is not a skill that is traditionally assessed regularly in school as part of the normal curriculum, many of these assessments have come from experimental studies where the skills are practiced in a lab environment that is somewhat artificial or contrived, in the sense that it is not connected to school learning.

For example, some metacognition studies focus on metamemory. Flavell (1979) describes assessment tasks that asked children to study a set of items until they were sure they could remember them completely. Children were then tested on their ability to recall all the items. Another common task was to read a set of written instructions and indicate any omissions, mistakes, or areas of ambiguity. Schneider (2008) observes that the most studied type of procedural metamemory is self-monitoring. Assessments designed to capture this ability include ease of learning judgments, judgments of learning, and feelings of knowing. For example, ease of learning judgments typically ask students to study a set of test materials for a short amount of time and then assess their abilities to remember the material. After the students are tested on the material, their performances are compared to their initial predictions. Feeling of knowing judgments ask subjects to identify by name a series of pictures; when subjects cannot recall the word for a particular picture, they are asked whether they would be able to identify the word if it were shown to them. These predictions are then compared to their actual abilities to recognize the correct term among a list of options. Another indicator of procedural metamemory is allocation of study time. If subjects are given sets of material to memorize and are observed to allocate more study time to learning difficult concepts, this is an indication of strong self-monitoring abilities.

Finally, researchers have often investigated young children's theory of mind using location-false belief, contents-false belief, deceptive pointing, and appearance-reality tasks

(Carlson & Moses, 2003). Each of these tasks involves cognitive conflict in some way, in the sense that successful performance requires subjects to suppress impulsive responses and to produce a response that is incompatible with the dominant response. For example, in one standard location-false belief task, a child observes two puppets interacting. One puppet places an object in a specific location and then “leaves the room.” The second puppet moves the object to another, hidden location. When the first puppet re-enters the room, the subject is asked to predict where he will look for the object—in the original location or in the new, actual location. Similarly, in a standard contents-false belief task, children are shown a common, brand-name box of bandages and asked to predict what is inside. The box is then opened and children are shown that it actually contains crayons. Another investigator then enters the room and is shown the closed box. Children are asked to speculate about what the second experimenter believes is in the box. Deceptive pointing involves a similar setup where students observe an object being hidden in various locations and are then asked to deceive a third person about the object’s location by “deceptively” pointing to a null location. Finally, a standard appearance-reality task attempts to train children to respond “day” when shown a picture of the moon and “night” when shown a picture of the sun.

Another common method for capturing metacognition is the use of self-report questionnaires or rating scales. Kramarski and Mevarech (2003) used a metacognitive questionnaire, assessing both general metacognition and what they called domain-specific metacognition (math strategies). Students were presented with a range of strategies and asked to indicate whether and how often they used the strategies, employing a 5-point Likert scale that ranged from “never” to “always.” Cross and Paris (1988) assessed children’s metacognitive reading skills using two different measures. The Reading Awareness Interview was designed to

assess children's awareness about reading in three areas: evaluation of task difficulty and one's own abilities, planning to reach a goal, and monitoring progress towards the goal. The interview contained 33 Likert-scaled items and 19 open-ended questions. The authors also used a strategy rating task; strategies were read aloud and children were asked to rate the effect of each on reading comprehension using a 7-point scale ranging from "hurts a lot" to "helps a lot."

Sperling et al. (2002) administered the Junior Metacognitive Awareness Inventory to students in grades 3-9. Students in grades 3-5 responded to Version A, which was a self-report inventory with 12 statements such as, "I ask myself if I learned as much as I could have when I finish a task." Students rated the frequency with which they used each strategy using a 3-point scale ranging from "never" to "always." Students in grades 6-9 responded to Version B, which contained similar statements but more of them (18 total items). Students responding to Version B used a 5-point Likert scale to rate their agreement with each statement. Empirical results generally support the approach to defining metacognition as including both knowledge and regulation in that researchers obtained a 2-factor solution, with items loading essentially as hypothesized. Student performance on these measures correlated positively and significantly with other measures of metacognition, particularly for students in grades 3-5 (thus providing evidence of convergent validity). At the same time, scores on Versions A and B correlated only slightly with student achievement, thus providing discriminant validity evidence.

A few studies have attempted to measure metacognition in a way that is more connected to in-school learning. For example, Hennessey (1999) studied metacognition in the context of school science. Students working in collaborative groups were taught to represent their science conceptions graphically, and were expected to be able to perform the following skills:

- state their own beliefs about the topic
- consider the reasoning used to support their beliefs
- look for consistency among their views
- explore the implications of their views over a wide range of activities while looking for commonalities
- explore abstract concepts, propositions, or theories by constructing physical representations of their views
- distinguish between plausible, intelligible, and fruitful (grades 4-6) or distinguish between understanding an idea and believing it to be true (grades 1-3)
- explicitly talk about the status of their conceptions (grades 4-6)
- explicitly refer to their own thinking or learning

Hennessey developed six categories to characterize the various levels of metacognition evident in students' discourse as they constructed or revised representations of their science conceptions. Hennessey used protocol analysis to code students' metacognitive behaviors according to the following scheme:

- conceptions – any metacognitive statements in which the student expresses his or her conceptions
- reasoning – any statements where the student refers to reasoning to explain his/her conceptions

- implications – any statements in which the student is considering implications or limitations of his/her conceptions
- thinking process – any statements in which the student is considering his/her thinking/learning process
- status – any statement in which the student is commenting on the status of his/her conceptions (i.e., evaluating intelligibility, plausibility, fruitfulness of the concept)
- conceptual ecology – statements in which the student refers to or specifically uses any components of his/her conceptual ecology

Whitebread et al. (2009) developed an observational checklist with 22 items to measure metacognition and self-regulation in children between the ages of 3 and 5. This checklist identifies a range of student behaviors—both verbal and nonverbal—theorized to represent metacognitive knowledge, metacognitive regulation, and emotional and motivational regulation. Teachers are to code metacognitive events observed during the course of individual or group learning by rating individual students on each behavior using a 4-point Likert scale ranging from “Always” to “Never.” The checklist, which was developed and subsequently validated in the classroom, has been found to have relatively high reliability, with 66-96% agreement between raters, depending on the level of the coding scheme used.

General Suggestions for Assessing Metacognition

A few researchers have offered general suggestions for measuring or assessing metacognition. For example, Schraw and Moshman (1995) favor verbal report methods because

they allow researchers to access aspects of thinking that are not directly observable. On the other hand, Whitebread et al. (2009) argue that observational methods have advantages over self-report and think-aloud methods. Observational approaches record actual learner behaviors, which enables nonverbal behaviors to be taken into account. Further, observational techniques can record social processes that may be important in acquisition of metacognitive skills. Kramarski and Mevarech (2003) recommend using instructional tasks that are complex, allow multiple representations of concepts, and afford students opportunities to identify and resolve conceptual conflicts. Finally, Perry (1988) notes that writing activities, especially those involving students in all stages of the writing process (planning, drafting, editing, and revising) offer ample opportunities for self-regulated learning.

Summary

Metacognition is a multidimensional set of skills that involve “thinking about thinking.” Metacognition entails two components: metacognitive knowledge and metacognitive regulation. Metacognitive knowledge includes knowledge about oneself as a learner and about the factors that might impact performance (declarative), knowledge about strategies (procedural), and knowledge about when and why to use strategies (conditional). Metacognitive regulation is the monitoring of one’s cognition and includes planning activities, monitoring or awareness of comprehension and task performance, and evaluation of the efficacy of monitoring processes and strategies. Insights experienced while monitoring and regulating cognition play a role in the development and refinement of metacognitive knowledge. In turn, cognitive knowledge appears to facilitate the ability to regulate cognition. The two are empirically related and may be integrated in the form of metacognitive theories, which are formal or informal frameworks for representing and organizing beliefs about knowledge.

Metacognition is related to a number of other constructs, including critical thinking and motivation. Critical thinking may be a component of metacognition or both concepts may be subsumed under the more general framework of self-regulated learning. At the very least, metacognition can be seen as a supporting condition for critical thinking to the extent that monitoring the quality of one's thought makes it more likely that one will engage in high-quality thinking. Motivation is the set of beliefs and attitudes that underlie the development and expression of metacognition. Thus, self-regulation includes the ability to manage and regulate affective states, and its effect on academic success is mediated by motivation. Children with better self-regulation of emotion experience more positive social relationships at school, which in turn increases their level of engagement and academic motivation. This improved motivation then enhances academic performance. Empirical research supports this link, as effortful control of affective states predicts future SAT scores, as well as reading and math abilities.

Early research tended to conclude that metacognition is a late-developing skill. The metacognitive capacity of preschool- and elementary-aged children is limited by several factors, including the development of executive functioning and verbal ability. For example, maturation of the portions of the brain responsible for executive functioning does not occur until 3-6 years of age, which parallels the emergence of skills such as inhibitory control. Inhibitory control is believed to be a foundational skill for theory of mind development. Theory of mind, which predicts subsequent metamemory, may in turn be dependent on the development of verbal reasoning skills. More recent research suggests that young children are capable of rudimentary forms of metacognitive thought, particularly after the age of 3. Preschool-aged children will demonstrate metacognitive behaviors, such as articulation of cognitive knowledge, regulation of thought, and regulation of emotional and affective states.

A number of researchers have proposed alternative models of metacognitive development over time. Although individual developmental models may vary, in general, they all postulate massive improvements in metacognitive ability during the first 6 years of life, with the most dramatic changes occurring between the ages of 3 and 4. Cognitive knowledge tends to emerge first, with regulation of cognition not appearing until much later. Metacognition improves with both age and appropriate instruction, with substantial empirical evidence supporting the notion that students can be taught to reflect on their own thinking. Researchers recommend a number of specific instructional strategies, including providing explicit instruction in both cognitive knowledge and cognitive regulation, using collaborative or cooperative learning methods, using tasks and activities that make student conceptions and beliefs visible, promoting awareness of metacognition through teacher modeling, and attending to the affective and motivational aspects of metacognition.

Finally, assessment of metacognition is challenging for a number of reasons: (1) metacognition is a complex construct, involving a number of different types of knowledge and skills; (2) it is not directly observable; (3) it may be confounded in practice with both verbal ability and working memory capacity; and (4) existing measures tend to be narrow in focus and decontextualized from in-school learning. Common methods for measuring metacognition include the somewhat artificial tasks typically used in controlled laboratory experiments, self-report methods such as questionnaires or rating scales, think-aloud approaches that attempt to make student thinking visible, and methods based on teacher observation of student learning. This latter category of approaches may have more ecological validity than the others, because it is somewhat independent of the student's verbal ability and working memory capacity, can include nonverbal metacognitive behaviors, can take into consideration social processes that may

be important for acquisition of metacognitive skills, and may be embedded in the context of instruction and learning.

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Metalearning and Recommender Systems: A literature review and empirical study on the algorithm selection problem for Collaborative Filtering



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ABSTRACT

The problem of information overload motivated the appearance of Recommender Systems. From the several open problems in this area, the decision of which is the best recommendation algorithm for a specific problem is one of the most important and less studied. The current trend to solve this problem is the experimental evaluation of several recommendation algorithms in a handful of datasets. However, these studies require an extensive amount of computational resources, particularly processing time. To avoid these drawbacks, researchers have investigated the use of Metalearning to select the best recommendation algorithms in different scopes. Such studies allow to understand the relationships between data characteristics and the relative performance of recommendation algorithms, which can be used to select the best algorithm(s) for a new problem. The contributions of this study are two-fold: 1) to identify and discuss the key concepts of algorithm selection for recommendation algorithms via a systematic literature review and 2) to perform an experimental study on the Metalearning approaches reviewed in order to identify the most promising concepts for automatic selection of recommendation algorithms.

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1. Introduction

Recommender Systems (RSs) were proposed to deal with the problem of information overload [5]. The basic idea is to embody a system with the ability to recommend to a specific user the most relevant items among a set of existing options. The success of these systems is clear in both academia and industry [25]. However, the recommendation problem is not without flaws. One of the current challenges is the lack of guidance regarding which RS algorithm would be more adequate for a given task, and, more importantly, why. Current strategies to deal with this problem involve the evaluation of every available algorithm for each problem to decide which one is more adequate. This is an expensive approach, not only regarding time, but also considering human and computational resources. An automatic alternative for algorithm selection that overcome such drawbacks is Metalearning (MtL).

MtL [6] uses Machine Learning (ML) techniques to obtain predictive models, which associate characteristics of tasks to the respective performance of algorithms. The methodology initially involves extracting characteristics from a dataset, named metafeatures, and assessing the relative performance of a group of algorithms, which will be used as metalabels.

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Afterwards, this information for several datasets is used to induce a predictive model able to represent the relationship between the metafeatures and metalabels of these datasets. If this model has a high predictive performance, it would will be able to predict the most promising algorithm without the overhead of running a full-fledged empirical evaluation and to explain why RS algorithms perform best/worst [41].

This work focuses first on providing a systematic literature review on the problem of algorithm selection for RSs. The related work is reviewed on the key dimensions required to solve the algorithm selection problem. In each dimension, the extent of the research conducted so far is discussed and lines of research for future work are suggested. Afterwards, the most suitable related work strategies for algorithm selection for Collaborative Filtering (CF) are experimentally evaluated. The experiments allow to compare the effects of the different metafeatures on the same experimental setup. A large experimental study of baselevel datasets, algorithms and evaluation metrics is conducted. Afterwards, each MtL strategy is implemented and evaluated on the same metalevel setup, i.e. same metatarget, meta-algorithms and evaluation measures. Finally, conclusions are drawn from the behavior of the current state of the art approaches with regards to several aspects of the algorithm selection problem.

This document is organized as follows: [Section 2](#) presents a brief review on RS, focusing on CF and the evaluation protocol. [Section 3](#) presents the methodology of algorithm selection using MtL. Next, [Section 4](#) presents the process for systematic review on the related work about algorithm selection for RSs. [Section 5](#) is responsible to present the empirical study performed on a subset of the Metalearning approaches discussed previously. [Section 6](#) highlights the final conclusions and points out future work directions.

2. Recommender Systems

This section presents the basic aspects of RSs, with a focus on CF recommendations. It also describes how the performance RSs are usually evaluated.

2.1. Overview

Several RSs have been proposed in the last decades. One of the main aspects that differentiates these systems is the followed approach. These strategies can be roughly divided into eight approaches: Collaborative Filtering (CF) [37], Content based Filtering [4], Social based Filtering [23], Knowledge based Filtering [4], Hybrid Filtering [7], Context-aware Filtering [1], Deep Learning-based Recommendations [20,44] and Group Recommendations (GR) [30]. Since the majority of the focus of the MtL studies lies on CF, only this strategy will be further discussed in this paper. Further information regarding the remaining strategies is available elsewhere [1,5,46].

2.2. Collaborative Filtering

CF recommendations are based on the premise that a user will like the items favored by a similar user, which is an user with similar preferences. It uses the (implicit or explicit) feedback from each individual user to recommended items among similar users [46]. Explicit feedback is a numerical value, proportional to the user's likeliness towards an item. Implicit feedback, on the other hand, derives a numerical value from the user's interactions with the item (click-through data, like/dislike actions, time spent on a task, etc.). The data structure used in CF is known as the rating matrix R . It is described as $R^{U \times I}$, representing a set of users U , where $u \in \{1, \dots, N\}$ and a set of items I , where $i \in \{1, \dots, M\}$. Each element R_{ui} is the user u feedback to item i . [Fig. 1](#) presents such matrix.

The CF algorithms are organized into two major classes: memory-based and model-based [5]. Memory-based algorithms apply heuristics to a rating matrix to compute recommendations, whereas model-based algorithms induce a model from a rating matrix and use the model to recommend items. Memory-based algorithms are mostly represented by Nearest Neighbor (NN) strategies, while model-based algorithms work with Matrix Factorization (MF). A memory-based algorithm follows 3 steps: 1) calculate the similarity between users or items, 2) create a neighborhood of similar users or items and 3) generate recommendations by sorting similar items. MF assumes that the original rating matrix values can be approximated by the multiplication of matrices with latent features that capture the underlying data patterns. Several MF algorithms have been successfully used in CF, namely, SVD++, SGD and ALS. Further information regarding this topic is available elsewhere [21].

2.3. Evaluation

The evaluation of RSs can be performed by offline and online procedures. Offline evaluation splits the dataset into training and testing subsets (using sampling strategies, such as k-fold cross-validation [18]) and assesses the performance of the trained model on the testing dataset (see [Fig. 2](#)). However, in order to compare the predicted and original values, there is an important difference from conventional k-fold cross validation: the test data must be split into hidden and observable instances.

Another important issue lies in the scopes for the evaluation metrics [25]:

- for rating accuracy, error metrics such as Mean Absolute Error (MAE) or Root Mean Squared Error (RMSE) must be used;

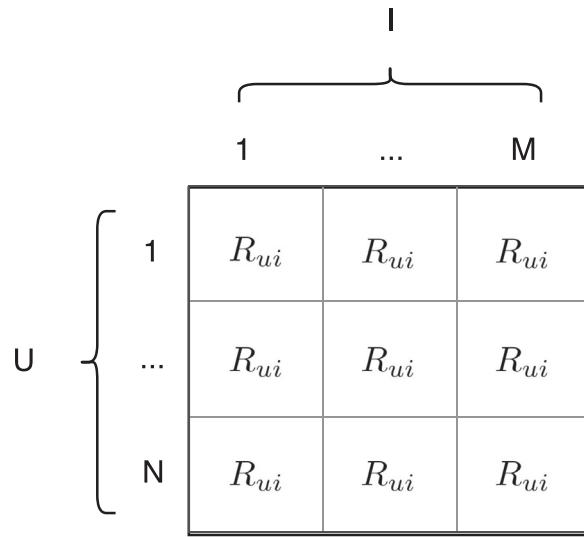


Fig. 1. Rating matrix.

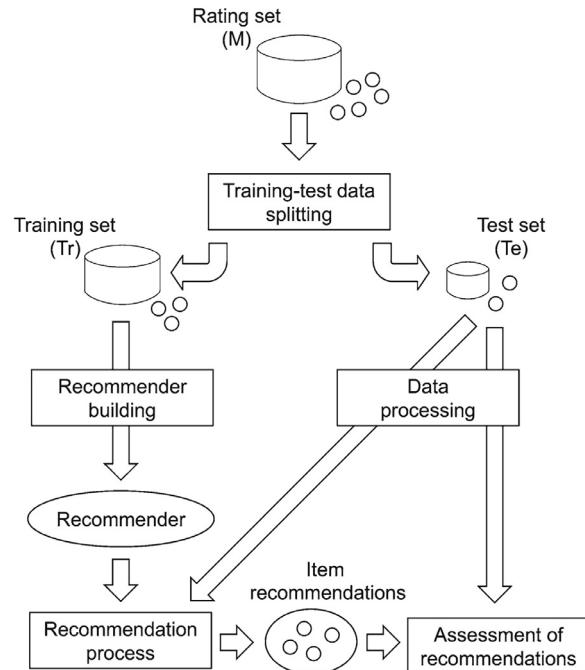


Fig. 2. Diagram of offline evaluation in RS [8].

- for classification accuracy, one must use Precision/Recall measures or Area Under the Curve (AUC);
- for ranking accuracy, the typical metrics are Normalized Discounted Cumulative Gain (NDCG), Mean Reciprocal Rank (MRR) and Expected Reciprocal Rank (ERR) [22,24]

The online evaluation arose from the necessity of assessing other aspects beyond those accessible offline, in which the actual input of a real user cannot be reproduced in a better way [18]. The most popular metric is the user acceptance ratio, which refers to the amount of items the user liked divided by the total amount of items recommended to the user. Additional online evaluation metrics are described elsewhere [43].

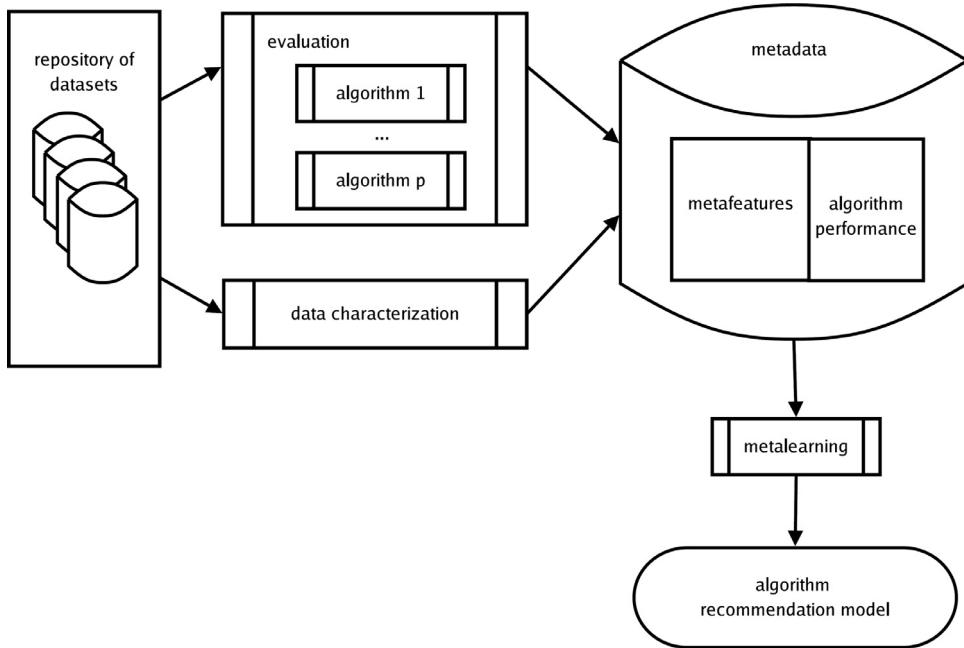


Fig. 3. Training process of a Metalearning process [6].

3. Metalearning

MtL is concerned with discovering patterns in data and understanding the effect on the behavior of algorithms [41]. It has been extensively used for algorithm selection [32,35,39]. The algorithm selection task can be viewed as a learning problem itself, by casting it as a predictive task. For such, it uses a metadataset, where each meta-example corresponds to a dataset. For each meta-example, the predictive features are characteristics (metafeatures) extracted from the corresponding dataset and the targets are the performance (metalabels) of a set of algorithms when they are applied to the dataset [6].

A MtL process addresses the algorithm selection problem similarly to a traditional learning process. It induces a metamodel, which can be seen as the metaknowledge able to explain why certain algorithms work better than others in datasets with specific characteristics. The metamodel can also be used to predict the best algorithm(s) for a new dataset/problem [38]. Fig. 3 presents the training stage of the MtL process.

One of the main challenges in MtL is to define which are the metafeatures that effectively describe how strongly a dataset matches the bias of each algorithm [6]. The MtL literature divides the metafeatures into three main groups [38,41]: statistical and/or information-theoretical, model-based and landmarks.

Statistical and/or information-theoretical metafeatures describe the dataset characteristics using a set of measures from statistics and information theory. These metafeatures assume that there are patterns in the dataset which can be related to the most suitable algorithms for these datasets. Examples include simple measures, such as the number of examples and features in the dataset, to more advanced measures, such as entropy, skewness and kurtosis of features and even mutual information and correlation between features [6].

Model-based characteristics are properties extracted from models induced from the dataset. In a classification or regression MtL scenario, they refer, for instance, to the number of leaf nodes in a decision tree [6]. The rationale is that there is a relationship between model characteristics and algorithm performance which cannot be captured from the data directly. For instance, a decision tree with an unusually large number of leaf nodes may indicate overfitting.

Finally, landmarks are fast estimates of the algorithm performance on the dataset. There are two different types of landmarks: those obtained from the application of fast and simple algorithms on complete datasets (e.g. a decision stump can be regarded as a simplified version of a decision tree) and those which are achieved by using complete models for samples of datasets, also known as subsampling landmarks [6] (e.g. applying the full decision tree on a sample).

4. Algorithm selection for Recommender Systems

The problem of algorithm selection was first conceptualized by Rice [33], which defined the following search spaces:

- the problem space P , representing the set of instances of a problem;
- the feature space F , containing measurable characteristics of the instances generated by a feature extraction process applied to an instance of P ;

- the algorithm space A , as the set of all suitable algorithms for the problem;
- the performance space Y , which represents the mapping of each algorithm to a set of performance measures;

Considering this framework, the problem of algorithm selection can be stated as: “*for a given problem instance $x \in P$, with features $f(x) \in F$, find the selection mapping $S(f(x))$ into the algorithm space A , such that the selected algorithm $\alpha \in A$ maximizes the performance mapping $y(\alpha(x)) \in Y$.*” [33].

In the scope of this work, the problem space P is a set of recommendation datasets, the feature space F is composed by the metafeatures used to describe the datasets, the algorithm space A contains all the available algorithms and the performance space Y is described by a set of suitable evaluation measures.

4.1. Methodology

In order to perform a systematic review on algorithm selection for RSs, several online databases were consulted: Elsevier's Scopus, Thomson Reuters's Web of Science, IEEE Xplore Digital Library, Google Scholar and ACM Digital Library. The keywords combined the keywords: “*Recommender System*”, “*metalearning*”, “*algorithm selection*” and “*performance prediction*”. This document reviews only approaches that relate the performance of RS algorithms with data characteristics.

4.2. Research questions

Considering the MtL workflow, the most important dimensions of the algorithm selection problem for RS were identified. The dimensions are split into base- and metalevels and are translated into Research Questions (RQ):

- **RQ1:** What is the coverage of recommendation strategies in MtL studies?
- **RQ2:** Are the public datasets used representative and enough?
- **RQ3:** Is the pool of recommendation algorithms suitable and complete?
- **RQ4:** How well are the RSs performance measures covered?
- **RQ5:** Are the metafeatures used diversified in nature and enough?
- **RQ6:** In the studies, what is the typical metatarget?
- **RQ7:** Which algorithms are employed in the metalevel?
- **RQ8:** Are the evaluation measures used in the metalevel suitable?

4.3. Related work

The literature provides a few approaches for the RS algorithm selection problem. The first work studies the CF algorithm selection problem by mapping the data onto a graph instead of a rating matrix [19]. Graph-dependent metafeatures are derived to select among NN algorithms. The selection process takes advantage of a domain-dependent rules-based model.

Other papers analyzed the rating matrix using statistical and/or information-theoretical metafeatures to select among NN and MF algorithms [2,13]. The problems were addressed as regression tasks, where the goal was to optimize the RMSE performance.

An alternative approach, using a decision tree regression model, was developed later [16]. It studied the underlying relationship between user ratings and neighborhood data and the expected error of the recommendations of a NN algorithm. This approach focused on describing metafeatures for users, instead of the entire dataset.

Another proposal looked to the co-ratings instead of the original ratings [26]. This extended the original data available in the rating matrix with relationships among users. It uses a regression model to predict the RMSE performance of NN and MF algorithms.

The algorithm selection problem was extended beyond CF, when a GR approach was proposed [49]. It used several classification algorithms to rank vote aggregation algorithms. For such, it derives domain-dependent metafeatures and relates them with the performance of the algorithms in terms of error.

The most comprehensive MtL study for CF algorithm selection studies the selection of MF algorithms using an extensive experimental setup [10]. It considers multiple algorithms and evaluation metrics at both the base- and metalevels. Furthermore, it proposed a set of systematically generated metafeatures which extends the union of almost all the ones available in the previous literature.

The related work for the literature review is presented in Table 1. Each work is described in terms of the RQ identified earlier. Some RQs are sub-divided, using the notation:

- The baselevel algorithms (RQ3) are organized by type - Heuristics (H), Nearest Neighbors (NN), Matrix Factorization (MF) and others (O).
- The base-evaluation measures (RQ4) are organized into error based (E), classification accuracy (CA) and ranking accuracy (RA).
- The metafeatures (RQ5) are divided according to the subject evaluated: user (U), item (I), ratings (RT), data structure (S) and others (O).
- The metatargets (RQ6) are: 1) best algorithm (BA), 2) ranking of algorithms (RA) and 3) performance estimation (PE).
- The metalevel algorithms (RQ7) use classification (C), regression (RG) or other (O) types of algorithms.

Table 1

Summary table on the algorithm selection problem for RS. Each column refers to the RQ identified in this work (see [Section 4.2](#)): RQ1 (recommendation strategies), RQ2 (baselevel datasets), RQ3 (baselevel algorithms), RQ4 (baselevel evaluation measures), RQ5 (metafeatures), RQ6 (metatarget), RQ7 (meta-algorithms) and RQ8 (metalevel evaluation). RQ 3, 4, 5, 6 and 7 are divided in several categories (see [Section 4.3](#)).

Ref.	Baselevel							Metalevel											
	RQ1		RQ2		RQ3			RQ4			RQ5			RQ6		RQ7		RQ8	
	H	NN	MF	O	E	CA	RA	U	I	RT	S	O	C	RG	O				
[19]	CF	3	2	2	—	—	—	3	1	—	—	2	2	BA	—	—	1	AUC	
[2]	CF	4	—	2	1	—	1	—	—	1	1	1	3	—	PE	—	1	—	Correlation
[13]	CF	1	1	2	1	1	1	—	—	3	—	—	—	—	PE	—	1	—	Correlation
[16]	CF	3	—	1	—	—	1	—	—	11	—	—	—	—	PE	—	1	—	MAE
[26]	CF	4	—	1	1	—	1	—	—	—	—	—	3	—	PE	—	1	—	Correlation
[49]	GR	4	11	—	—	—	1	—	—	5	—	—	—	—	RA	4	—	—	MRR
[10]	CF	32	4	—	13	—	3	1	3	30	30	10	4	—	BA	10	—	—	Accuracy

4.4. Discussion

This section analyses the results presented in [Table 1](#) regarding the several aspects identified in the RQ (see [Section 4.2](#)).

4.4.1. Recommendation strategies

Since this research area is still in the early stages (all works were published in the last 6 years), it is expected that only a few RS strategies would have been studied. In fact, like in the RS research area, the majority of the researches has been performed on CF. This is justified by the lack of public frameworks beyond this recommendation strategy. The exception is a recent study on the algorithm selection problem for Group Recommendation (GR) [49]. Therefore, it is essential to 1) expand the scope of RS strategies studied and 2) perform a deeper analysis of the algorithm selection problem for CF.

4.4.2. Datasets

Most related work use at most 4 datasets to investigate algorithm selection, with the exception of the most recent work [10]. While on some cases this may be acceptable if the problem is appropriately modeled (for instance, select the best algorithm for each user instead of per each dataset [16]), this small number is usually a drawback. In fact, algorithm selection strategies must use a large amount of diverse datasets to ensure a proper exploration of the problem space P . This dimension must be improved, although there are few public datasets.

The public datasets used in the related work are: Amazon Reviews [27], BookCrossing [50], Epinions [34], Flixter [48], Jester [15], LastFM [3], MovieLens [17], MovieTweetings [12], Netflix [29], TripAdvisor [42] and Yahoo! Music [45]. Only two works use private data [19,49], which are excluded from further analysis.

The results show a large variation in how frequent each dataset is used in these works. The most common dataset belongs to the MovieLens category (used 5 times out of 7). This follows the trend in the RS research area, where these datasets are considered benchmarks. The second choices fell on the Flixter, Jester and Netflix datasets. While the first two are used in about half of the works, the Netflix dataset is more frequent and should be present in more studies. It became popularity after a world-wide competition that finished in 2009 [21]. However, the main difficulty lies with the fact that the dataset is no longer available for download. The remaining datasets appear only once.

Although it is important to analyze the related work in terms of amount and source of the datasets, it is even more important to review some of their characteristics. The inspection of the datasets characteristics illustrates the following aspects: 1) the number of users and items is rather small when compared to the number of ratings, 2) the sparsity values are usually greater than 0.9 and 3) the most common rating scale ranges from 1 to 5. Overall, the datasets cover a wide range in terms of scale and structure of the rating matrix in CF. This shows that the collection of public datasets is representative, although not exhaustive. Several points need to be improved, including the analysis of different levels of sparsity and understanding the effects on the performance and to extend the types of scales used. These improvements can be obtained by creating artificial datasets. This can be achieved by applying permutations to the original datasets (maintaining some global characteristics), by creating entirely new data recurring to well-known distributions, by adding noise to the datasets or by creating artificial datasets using simulation [9].

4.4.3. Baselevel algorithms

The baselevel algorithms frequently used are distributed in the following categories: Heuristics (18), MF (16), NN (8) and Others (1). The fact that MF and NN approaches are abundant is expected, since they are the most commonly used in CF. The large amount of heuristics refers mostly to the GR approach, which studies 11 algorithms of this nature. In CF, heuristics are typically associated with naive approaches, such as random and most popular algorithms. It is also clear that newer studies change the focus from NN algorithms to MF. This is expected, since MF is now the standard in CF.

The most frequently used algorithms are user-based NN and SVD++, closely followed by item-based NN. This represents the most basic approaches for CF and are therefore available in a larger amount of recommendation platforms. Newer approaches, such as MF (besides SVD++), are usually more difficult to find in recommendation platforms. This is an important limitation, given MF's relevance. Averages and most popular algorithms are more common than a random approach. This is expected, since they are better baselines [21].

Although the algorithms used are suitable for CF, the authors do not know of any study that takes in account a complete and diverse pool of algorithms. Even the most recent and complete study fails in pursuing NN algorithms [10]. In order to properly explore the algorithm space A for CF, it is important to evaluate the new algorithms. Nowadays, there is a large number of resources to conduct experimental evaluations, specially for CF. However, none of them deals with the algorithm selection problem. A platform for model management that could integrate several RS algorithms and datasets, while providing faithful and fair evaluation would be the best solution to this problem. However, the closest systems are frameworks devoted solely to the evaluation of RSs [36].

4.4.4. Baselevel evaluation

Table 1 shows that most evaluation measures are error based (used in 6 out of 7 works). On the other hand, accuracy measures (either classification or ranking based) are only used in 2 works. The most frequently used error measures are RMSE and MAE, classification accuracy evaluated through precision, recall and AUC and ranking accuracy assessed by MRR and NDCG. The evaluation procedures usually assess only one aspect of the recommendation process, contradicting the guidelines from the RS literature [18]. In fact, only 2 works expanded the evaluation scope [10,19]. This clearly demonstrates the incompleteness of the evaluation in the related work. Further investigations are required to improve the exploration of the performance space Y , including increase the scope of offline evaluation measures and perform the same studies using online rather than offline evaluation procedures. The first can be achieved by using recent, yet not fully validated, measures. These try to assess non standard dimensions of the RS problem such as novelty, satisfaction and diversity. Also, online evaluation measures could be used to compare the actual feedback with the predictions, since they are claimed to be better.

4.4.5. Metafeatures

The metafeatures used in the related works are all statistical and information-theoretical measures. They can be organized into several categories: user (50), item (31), ratings distribution (11), data structure (12) and others (2). Most of them focuses on users. In fact, some research uses only metafeatures of this dimension of the problem [13,16,49]. Characteristics related to the data structure are also common and are available in 4 out of 7 works. One work used all previous metafeatures in an user co-occurrence matrix [26].

The number of metafeatures used usually ranges from 3 to 11, with only one exception that increases this number to 74 [10]. However, this is not necessarily an advantage. A smaller number avoids the curse of dimensionality and is more suitable when a small number of baseline algorithms are evaluated. However, assuming the existence of more recommendation algorithms, further and more diverse metafeatures should be studied to properly explore the feature space F .

The analysis of metafeatures in a deeper level allows us to understand which type of statistical and information-theoretical measures were used in the related work. The functions used are mostly ratios, averages and sums. This is expected, since they are the simplest metafeatures found in the MtL literature. Entropy, Gini index and standard deviation appear in the second position (in 3 works). All other functions appear only once.

Despite the fact that diverse metafeatures are proposed, few studies look towards different aspects of the problem. In fact, 4 studies focus their metafeatures on a single subject, which typically is the user. Plus, there are few examples of metafeatures that look towards relationships between the different subjects of the problem. This makes difficult to find complex patterns in the data, restricting the metaknowledge extracted. Recent works have successfully extended the nature and amount of metafeatures, improving dataset characterization for CF algorithm selection. These extensions include: 1) propose and adapt new metafeatures for other RS strategies; 2) propose problem-specific (and eventually domain-specific) metafeatures and 3) study new metafeatures besides statistical and/or information-theoretical, such as for instance, landmarks. This list is by no means exhaustive, since it is difficult to anticipate the necessities to properly describe the datasets of other RS problems besides CF. It is especially difficult when it comes to guarantee their informative power.

4.4.6. Metatarget

Related work on CF algorithm selection has adopted several metatargets. The most common is the performance estimation (PE), available in 4 out of 7 works. There are also two examples of best algorithm (BA) and ranking (RA) selections. Although recent works have looked beyond PE [10,49], real applications can benefit from the use of BA or RA due to interpretability issues.

4.4.7. Metalevel algorithms

Usually, only one algorithm is used in the metalevel. This algorithm must match the required metatarget. As can be seen in **Table 1**, when PE is used as metatarget, regression algorithms are used (mainly linear regression algorithms). For BA and RA, popular classification algorithms, like rule based classifiers, Naive Bayes, SVM and kNN, are used. An exception happens when a custom procedure based on rules is used [19]. Although the number of algorithms used in the metalevel does not have the same impact as the number used in the baselevel, the use of a larger and more diverse set of algorithms in the

metalevel increases the chances of uncover hidden relationships in the metadataset. Only two studies using more than one algorithm in the metalevel [10,49]. A relevant future work is the application of RS on both the base- and metalevel. Although this topic has not received any attention so far for the selection of recommendation algorithms, it has been successful in other domains. Such works are important to understand whether MtL approaches are indeed the best way to tackle the algorithm selection problem.

4.4.8. Metalevel evaluation

The last RQ focuses on the evaluation measures used in the metalevel. Once again, these must be in conformity with the metatarget and meta-algorithm. This is noted by the usage of error based measures or correlation assessments for PE [2,13,16,26], classification accuracy measures for BA [10,19] and ranking accuracy measures [49]. One can conclude that all related work performs validation for the algorithm selection task, while using suitable measures.

4.5. Summary

After reviewing in extent each key topic of the algorithm selection problem for CF, we present the key conclusions found:

- With the exception of one study on Group Recommendation, only CF has been studied on the algorithm selection problem.
- The public datasets are representative (although not exhaustive) and enough in recent works. However, previous studies use only few datasets.
- The pool of recommendation algorithms studied in algorithm selection studies is always suitable, but never complete.
- Most approaches evaluate CF with a single measure. However, recent studies are shifting the paradigm towards combining evaluation measures.
- Although a diverse set of metafeatures is available, the related works typically use few metafeatures.
- Although the typical metatarget is performance estimation, the trend has shifted towards choosing the best algorithm.
- Despite most studies working with regression algorithms to build metamodels, the change in metatarget has fueled the shift in meta-algorithms.
- Suitable metalevel evaluation measures were used in all related works.

5. Empirical study

As seen in the literature review, most related work use small scale experimental setups, which prevent the extraction of generic conclusions for RS. Furthermore, the datasets and algorithms used are different, making it difficult to quantitatively assess the merits of each approach. The main goal of this empirical study is to replicate the MtL approaches used by related works and to compare their performances on the same experimental setup. Thus, the baselevel experiments are constant for all approaches, and so are the meta-algorithms, metatarget and metalevel evaluation measures. The only difference is the set of metafeatures employed by each independent algorithm selection approach. More formally, the search spaces P , A and Y are fixed, while space F varies.

5.1. Related work

In order to choose the strategies which will be replicated in this experimental study, certain requirements must be established to ensure a fair evaluation:

- The recommendation strategy must be the same: this study will devote its attention to CF, since it is the most popular. This filters the approach for GR [49], since the metafeatures cannot be reproduced for the CF domain.
- The metafeatures must be specific to the dataset and not to users: the goal here is to compare strategies that select the best algorithm for a whole dataset. Therefore, studies which devotes attention to the selection of algorithms per CF user should be ruled out [13,16]. However, studies with adaptations, by assuming average values for the entire dataset, are kept. For these metafeatures, samples of users are used, whose size is set as the maximum between the total number of users and 1000.
- The metafeatures must reflect the characteristics of either implicit or explicit feedback datasets: since the majority of approaches are designed for explicit feedback, the others are filtered [19]. This is required because the comparison of metafeatures for different rating scales would yield unfair and unreliable results.

In order to formalize the strategies presented, this study takes advantage of a systematic metafeature generation framework [31]. The framework requires three main elements: object o , function f and post-function pf . The process applies the function to the object and, afterwards, the post-functions to that outcome in order to generate a single metafeature value. Thus, this framework can be represented using the following notation: $\{o.f.pf\}$. Next, the different metafeatures strategies are presented, while formalized in this framework.

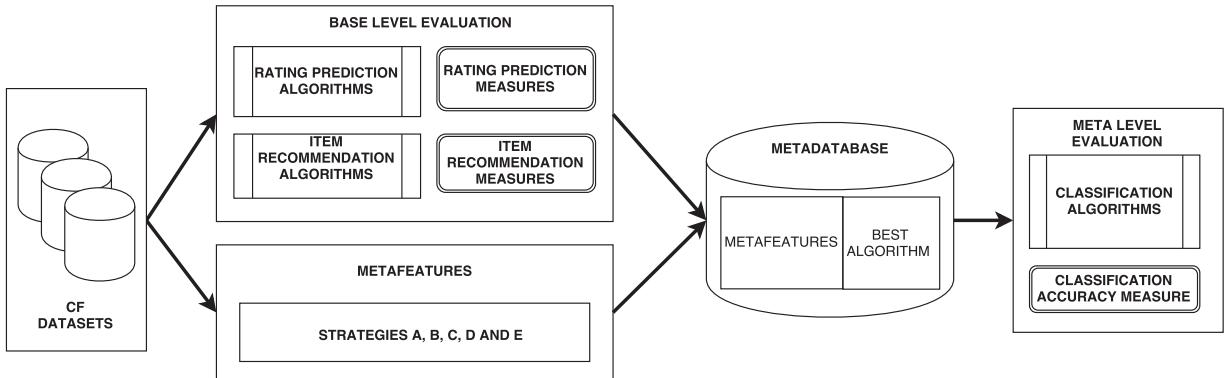


Fig. 4. Experimental procedure. This is an adaptation of Fig. 3 to the experiments carried out in this work.

5.1.1. Strategy A

This strategy generates metafeatures using the systematic framework [10]. It considers the objects o dataset, user and item and applies several functions f to characterize these objects: original ratings, sums of ratings, counts of ratings and average ratings. The post-functions pf used are maximum, minimum, mean, standard deviation, median, mode, entropy, Gini index, skewness and kurtosis. Details regarding the calculation of these functions are available elsewhere [28,40]. Additionally, this strategy includes 4 simple statistics: number of users, items, ratings and matrix sparsity. This results in 74 metafeatures, which were reduced by correlation feature selection, ending up with: *dataset.ratings.kurtosis*, *dataset.ratings.standard_deviation*, *dataset.nusers.Ø*, *dataset.sparsity.Ø*, *item.count.kurtosis*, *item.count.minimum*, *item.mean.entropy*, *item.sum.maximum*, *user.mean.minimum*, *user.sum.kurtosis*, *user.mean.skew* and *user.sum.entropy*.

5.1.2. Strategy B

This strategy [26] creates an auxiliary data structure from which the metafeatures are extracted. This structure, known as co-ratings matrix, is created by 1) random sample of users in the original ratings matrix, 2) assigning users to different equivalence classes (EC) depending on the number of ratings assigned and 3) creating a co-ratings matrix that compares each pair of equivalence classes by the average number of common co-rated items. The metafeatures are: *dataset.sparsity.Ø*, *EC.co-ratings.gini* and *EC.co-ratings.entropy*.

5.1.3. Strategy C

This strategy extracts the following metafeatures directly from the dataset [2]: *dataset.density.Ø*, *item.count.gini*, *item.count.skewness*, *user.count.gini*, *user.count.skewness* and *dataset.ratings.variance*.

5.1.4. Strategy D

One of the strategies that required adaptation for this experimental study looks at the problem as the selection of algorithms per user [16]. The adaptations involved averaging values of metafeatures among all users in the dataset and working with samples of users for metafeatures with high computational requirements. The complete list of metafeatures used in the strategy is: *user.mean.mean*, *user.count.mean*, *item.count.mean*, *user.standard_dev.mean*, *item.mean.mean*, *user.neighbours.mean*, *user.average_similarity.mean*, *user.clustering_coef.mean*, *user_coratings.jaccard.mean*, *user.TFIDF.mean* and *item.entropy.mean*.

5.1.5. Strategy E

The other strategy that approached the algorithm selection on user level was also adapted [13]. However, due the simpler nature of the metafeatures used, it was required only to average the values across users. The metafeatures produced are: *user.count.mean*, *user.mean.mean* and *user.variance.mean*.

5.2. Experimental procedure

We present now the experimental procedure used to compare the merits of the several metafeatures strategies presented earlier. Fig. 4 presents the base- and metalevels in terms of data, algorithm and evaluation measures. Next we present each level in detail.

5.2.1. Baselevel

The baselevel experiments refer to the CF problem, where a collection of datasets is evaluated on a pool of suitable algorithms. The 38 datasets used are split up into several domains, namely Amazon Reviews [27], BookCrossing [50], Flixter [48],

Table 2
Summary description about the datasets used in the experimental study.

Dataset	#users	#items	#ratings
Amazon Apps	132,391	24,366	264,233
Amazon Automotive	85,142	73,135	138,039
Amazon Baby	53,188	23,092	91,468
Amazon Beauty	121,027	76,253	202,719
Amazon CD	157,862	151,198	371,275
Amazon Clothes	311,726	267,503	574,029
Amazon Digital Music	47,824	47,313	83,863
Amazon Food	76,844	51,139	130,235
Amazon Games	82,676	24,600	133,726
Amazon Garden	71,480	34,004	99,111
Amazon Health	185,112	84,108	298,802
Amazon Home	251,162	123,878	425,764
Amazon Instant Video	42,692	8882	58,437
Amazon Instruments	33,922	22,964	50,394
Amazon Kindle	137,107	131,122	308,158
Amazon Movies	7278	1847	11,215
Amazon Office	90,932	39,229	124,095
Amazon Pet Supplies	74,099	33,852	123,236
Amazon Phones	226,105	91,289	345,285
Amazon Sports	199,052	127,620	326,941
Amazon Tools	121,248	73,742	192,015
Amazon Toys	134,291	94,594	225,670
Bookcrossing	7780	29,533	39,944
Flixter	14,761	22,040	812,930
Jester1	2498	100	181,560
Jester2	2350	100	169,783
Jester3	2493	96	61,770
Movielens 100k	94	1202	9759
Movielens 10m	6987	9814	1,017,159
Movielens 1m	604	3421	106,926
Movielens 20m	13,849	16,680	2,036,552
Movielens Latest	22,906	17,133	2,111,176
MovieTweetings latest	3702	7358	39,097
MovieTweetings RecSys2014	2491	4754	20,913
Tripadvisor	77,851	10,590	151,030
Yahoo! Movies	764	4078	22,135
Yahoo! Music	613	4620	30,852
Yelp	55,233	46,045	211,627

Jester [15], MovieLens [17], MovieTweetings [12], Tripadvisor [42], Yahoo! Music and Movies [45] and Yelp [47]. It should be noted that a domain may contain multiple datasets. Table 2 presents the datasets and some of their basic characteristics.

Experiments were carried out with MyMediaLite [14]. Two types of CF problems were addressed: Rating Prediction (RP) and Item Recommendation (IR). While in RP the goal is to predict the missing rating an user would assign to a new instance, in IR the goal is to recommend a list of ranked items matching the user's preferences. Since the problems are different, so are the algorithms and evaluation measures. The following CF algorithms were used in this work for the RP problem: Matrix Factorization (MF), Biased Matrix Factorization (BMF), Latent Feature Log Linear Model (LFLLM), SVD++, 3 variants of Sigmoid Asymmetric Factor Model (SIAFM, SUAFM and SCAFM), User Item Baseline (UIB) and Global Average (GA). In the case of IR, the algorithms used are BPRMF, Weighted BPRMF (WBPRMF), Soft Margin Ranking MF (SMRMF), WRMF and Most Popular (MP). Nearest neighbor algorithms are excluded due to incompatibility with the size of the datasets.

In IR, the algorithms are evaluated using the ranking accuracy metric Normalized Discounted Cumulative Gain (NDCG) and the classification accuracy metric Area Under the Curve (AUC). In the case of RP, the algorithms are evaluated using the error based measures Root Mean Squared Error (RMSE) and Normalized Mean Absolute Error (NMAE). All performances were assessed using 10-fold cross-validation. Following the standard approach in Mtl research, the algorithms were trained using the default parameters suggested in the literature or the implementation used. By not tuning the parameters of the baselevel algorithms, the optimal performance of each algorithm is not obtained. However, it prevents us from biasing the performance results in favor of any of the algorithms, thus ensuring a fair assessment.

5.2.2. Metalevel

The metalevel setup includes the metafeatures, the metatarget and the measures used to evaluate the metamodels. The metafeature extraction process involves applying all strategies discussed in Section 5.1 to all CF datasets listed in Table 2. The outcome is 5 different sets of metafeatures.

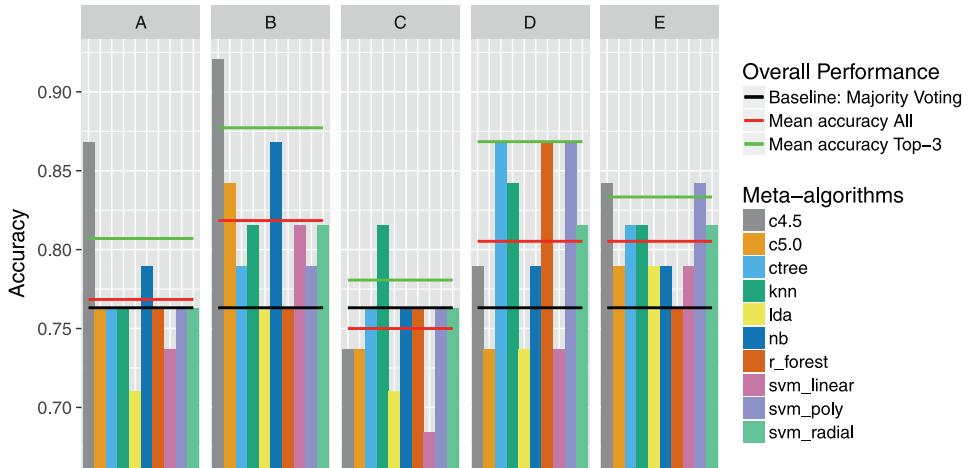


Fig. 5. Performance of the metafeature strategies on the AUC metatarget.

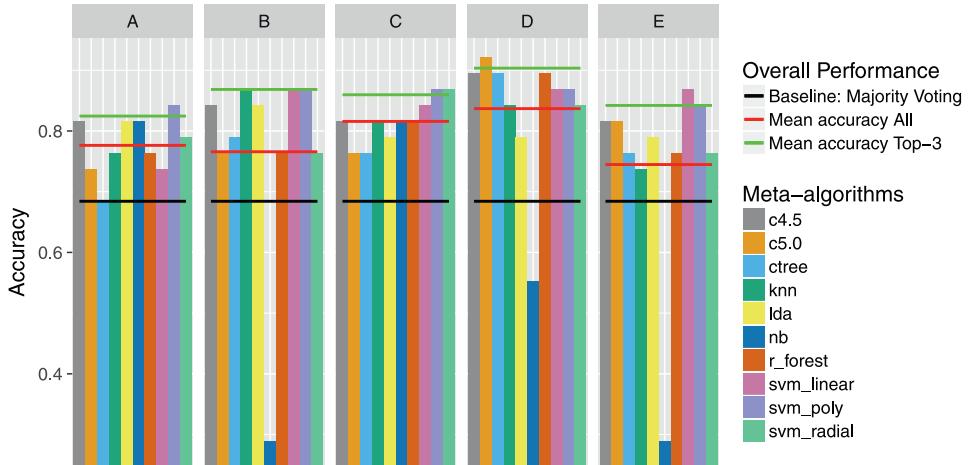


Fig. 6. Performance of the metafeature strategies on the NDCG metatarget.

The metatarget is built by identifying the best algorithm for each specific dataset. Since we use different baselevel evaluation measures, then it is expected that different algorithms are selected as the best choice for a specific dataset for different measures. Thus, NDCG and AUC are used to select the best algorithms in IR tasks, while in RP tasks, RMSE and NMAE are used. This creates 4 different metatargets, which when combined with the 5 different sets of metafeatures, leads to the total amount of 20 metadatasets to be used in the algorithm selection problem.

These problems are addressed as classification tasks. We tested 11 algorithms on each of those metadatasets, with different biases: ctree, C4.5, C5.0, kNN, LDA, Naive Bayes, SVM (linear, polynomial and radial kernels), random forest and a baseline algorithm: majority vote. The majority vote does not take into account any metafeatures and always predicts the class which appears more often. Since the metadatasets have a reduced number of examples, the accuracy of the metalevel algorithms was estimated using a leave one out strategy.

5.3. Results

5.3.1. Metalevel accuracy

The metalevel performance of the strategies regarding the accuracy of the metamodels in each metatarget is presented in Figs. 5–8. In each figure, all strategies are presented alongside each other, to facilitate their comparison. Within each figure, the accuracy of the best tuned meta-algorithms are presented. There are also indications regarding the baseline, i.e. majority voting. Thus, a model whose performance is lower than the baseline, is not considered informative. Two other reference values are also presented: the mean accuracy of all algorithms and the mean accuracy of the top 3 best meta-algorithms. Their purpose is to understand the robustness of the strategies on the average and best case scenarios, respectively.

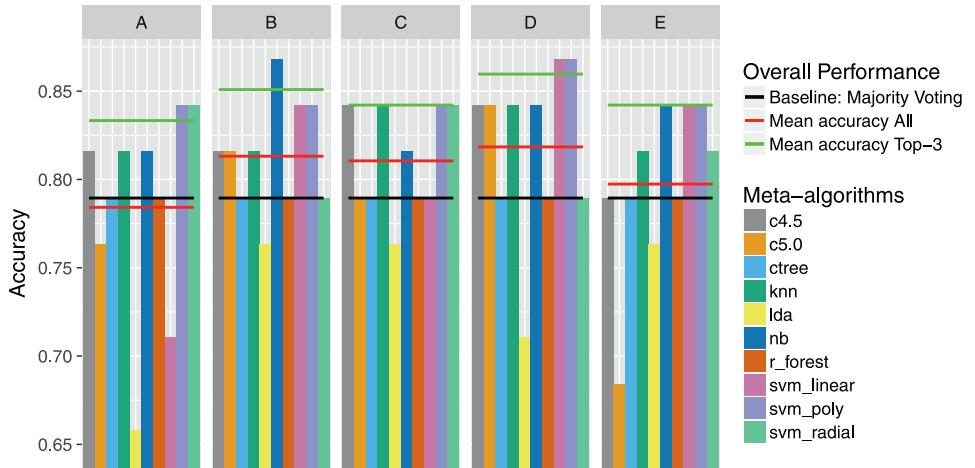


Fig. 7. Performance of the metafeature strategies on the RMSE metatarget.

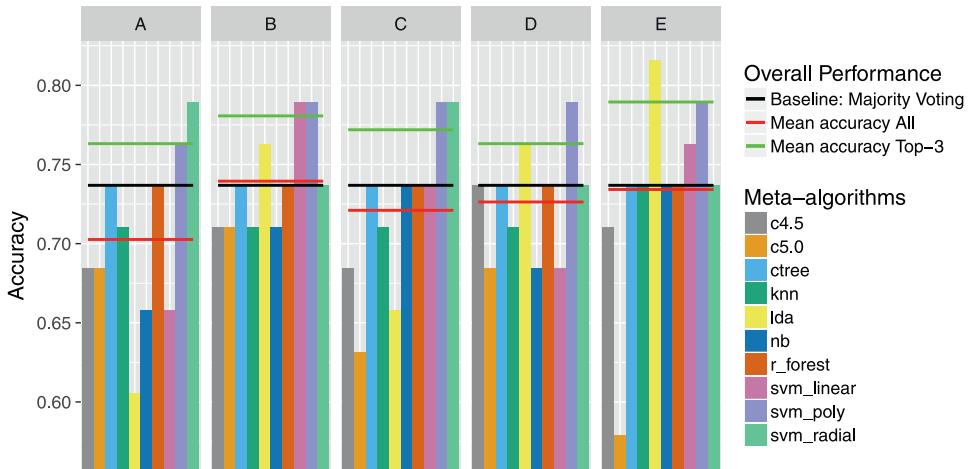


Fig. 8. Performance of the metafeature strategies on the NMAE metatarget.

Regarding Fig. 5, one can observe that all strategies except C have average performances above the baseline. Strategy C has a poor performance, since only one of the meta-algorithms (knn) beats the baseline. This strategy is also responsible by the worst performance, obtained with SVM with linear kernel. Strategy A barely beats the baseline, since two algorithms score below and six have the same performance of the baseline. This strategy only works with the models built with c4.5 and Naive Bayes. All remaining strategies have comparable performance, although strategy B seems slightly better. One important aspect is the performance of the c4.5 algorithm, which obtains the highest performance across all strategies. In terms of the average performance of the top 3 models, all strategies outperform the baseline. However, strategies B and D have higher performance, but with different algorithms. While the best algorithms in B are c4.5, c5.0 and Naive Bayes, in D they are ctree, random forest and SVM with polynomial kernel.

The performance results for the NDCG metatarget are presented in Fig. 6. Here, all strategies beat the baseline both in terms of average of all models and average of the best 3 models. In fact, there are only three occasions in which the baseline is not beaten: for the algorithm Naive Bayes in strategies B, D and E. The strategy with the best performance in both types of averages is D. It has the 4 best models found for this metatarget (c4.5, c5.0, ctree and random forest). The worst strategy by average of all algorithms is E, although this is mainly due to the low performance of the Naive Bayes algorithm. In terms of the average of the top 3 algorithms, strategy A performs slightly worse than the others. However, the worst algorithm in this strategy is the ctree, whose performance is similar to the baseline.

Fig. 7 presents the results for the RMSE metatarget. In terms of the average performance of all algorithms, A is the worst, since it is the only to score below the baseline. This is fueled by the performance of three algorithms (c5.0, LDA and SVM with linear kernel). The best strategies in this case are B, C and D, with low variation on the performance results, although all have one algorithm that was unable to beat the baseline: LDA. In terms of the performance of the top 3 algorithms, all

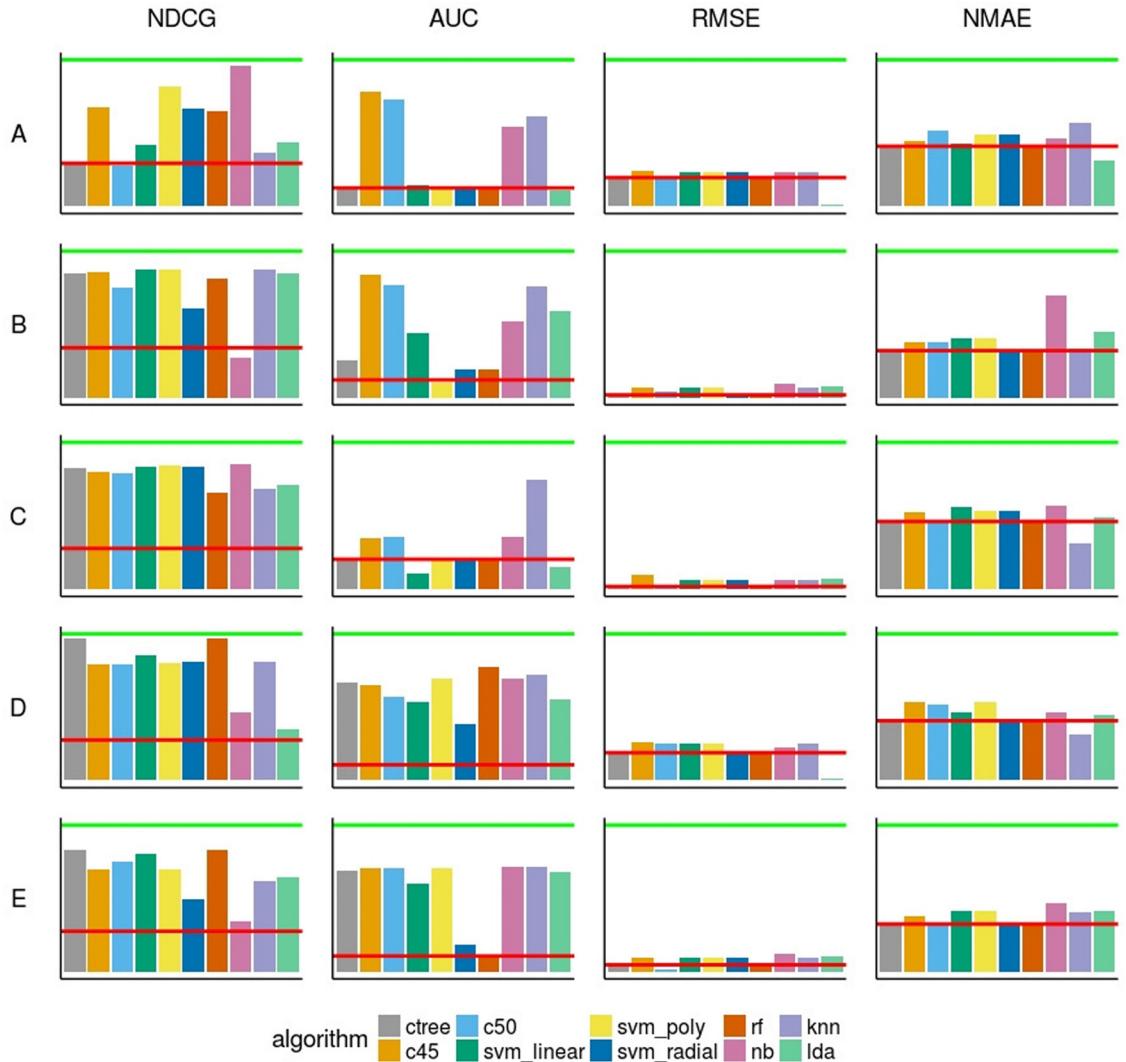


Fig. 9. Impact of meta-algorithms on the baselevel performance.

strategies yield good results, well above the baseline. The best and second best strategies in this case are D (with algorithms SVM with linear and polynomial kernels) and B (achieving highest performance with Naive Bayes), respectively.

Finally, the accuracy results for the NMAE metatarget are presented in Fig. 8. This metatarget has the worst results when considering the average accuracy of all models per strategy: four strategies present values below the baseline and only strategy B has a slightly higher accuracy, which may not be significant. In this metatarget, several algorithms perform poorly, such as the examples of the c5.0 for strategy E and LDA in strategy A. On top of this, at most 3 algorithms per strategy are able to beat the baseline. The only algorithm to beat the baseline in all strategies is the polynomial SVM. When the comparison considers the average performance of the top 3 algorithms, the scenario changes: all strategies yield good results. The best results are achieved with strategy E and algorithm LDA.

5.3.2. Baselevel impact

An important aspect to evaluate in Mtl problems is the impact of the metamodels trained on the baselevel performance. For such, the metamodels are evaluated by the performance of the baselevel algorithm predicted as the best in each dataset. The values are then averaged to obtain a single value that depicts the overall performance of the metamodel across all datasets. In these comparisons, two elements are crucial: the performance provided by the baseline metamodel (i.e. majority voting), the lower bound, and the so called oracle, which contains the performance of the actual best algorithm, the upper bound. This analysis is important to understand the real value of the metamodels and especially since it is missing in the original works.

Table 3
Computational time required for the extraction of each type of metafeature strategy.

Strategy	Total time (seconds)	Average time (seconds)
A	47.75	1.26
B	11957.95	314.68
C	4.64	0.12
D	35167.35	925.46
E	259.73	6.83

Fig. 9 presents the results from all strategies across all metatargets. In each pair strategy-metatarget, the baselevel performance from all meta-algorithms is shown. The baseline and oracle results are presented as the red and green horizontal lines, respectively. The results were presented in a format to facilitate their readability. All values are independently scaled and the results for RMSE and NMAE were inverted to uniform the analysis process. Thus, although the goal is to minimize these measures, the inverted scale allows the following analysis: an algorithm is better than another if its performance is higher.

The results show that metatarget NDCG has the largest number of metamodules whose performance is better than the baseline. In fact, in all strategies, there is only one example below the baseline. On the other extreme, RMSE and NMAE present the worst results. Here, most algorithms perform similar to or worse than the baseline. In the case of RMSE, the gap between the best metamodules and the oracle is the highest. While the results for NDCG and NMAE are expected, the RMSE case is a surprise. It shows that although the metalevel accuracy for this problem is acceptable for a subset of models, the impact on the performance of the recommendation problem is low.

Regarding strategies, the results are overall balanced across metatargets. However, there are some exceptions, such as strategies C, D and E for metatarget NDCG and strategy D for metatarget AUC. In all these cases, the results from all algorithms score above the baseline. There is no pair strategy-metatarget whose baselevel performance of all algorithms is always equal to or lower than the baseline, although the performance of the best metamodules on the RMSE metatarget is just slightly above the baseline.

5.3.3. Computational cost

One important aspect to be evaluated in the comparison of metafeature strategies is the amount of time required for metafeature extraction. Table 3 presents the recorded values for the total and average amount of time required. While the first refers to the time required to extract all metafeatures for all datasets, the second indicates the average time for one dataset. This last value is an indicator of the time required for the application on a future new problem.

According to the results, strategies C, A and E are the fastest, respectively, and the only that seem feasible in terms of computational resources. These results are expected due to fact that their metafeatures are the simplest and require only the rating matrix to be produced. On the other hand, strategies D and B are the most time consuming. The reason behind it lies with the usage of alternative data structures and the extraction of more detailed metafeatures.

5.4. Discussion

The main observations from this empirical study are the following:

- All strategies outperform the baseline with regards to the average of the top 3 algorithms. However, in terms of average performance, the strategies only seem to be effective for the NDCG metatarget, while failing for the NMAE. Regarding AUC and RMSE, there is no clear pattern. These observations indicate that solving the CF algorithm selection problem using Mtl is feasible and an efficient alternative to the standard empirical study. However, it also sheds light on an important problem: the practitioner must decide what is the criteria to select the best algorithm, since the metatargets will reflect different behaviors. And if the metatargets are different, then different metafeatures are required to solve the problem.
- When comparing the average performances across metatargets, strategy D yields the best results, closely followed by B. Strategies A, C and E have the worst performances, although in different metatargets. The best strategies have in common the fact that they explore the datasets in more detail and focus the metafeatures (directly or indirectly) on the user interactions. This may be an indication that future work should look towards more complex metafeatures such as those used in these works.
- The best and worst meta-algorithms across metatargets appear to be the polynomial SVM and LDA, respectively. This can be seen by inspecting the top positions of each algorithm in each combination of strategy and metatarget. Other algorithms do not have such an evident pattern. It is hard to attempt to explain why does this phenomenon occur. Clearly the bias in the algorithms is the responsible factor, although the actual reasons are still unknown.
- In terms of baselevel impact, the strategies work well for the NDCG metatarget and poorly for RMSE. The performance in terms of strategies is comparable, although there are some special cases. This points to the importance of this type of

Table 4

Tukey's test *p*-values for the comparison among baseline, average of all algorithms and average of top 3 algorithms. The *p*-values are highlighted if the differences are significant, i.e. *p*-value 0.05.

Pairwise	AUC	NDCG	NMAE	RMSE	All
top3-avg	0.078571	0.003901	0.000024	0.000074	0.000474
base-avg	0.350451	0.000191	0.206408	0.0734732	0.030089
base-top3	0.006020	0.000001	0.000357	0.000003	0.000000

Table 5

Tukey's test *p*-values for the comparison among strategies. The *p*-values are highlighted if the differences are significant, i.e. *p*-value 0.05.

Pairwise	AUC	NDCG	NMAE	RMSE	All
B-A	0.060590	0.999934	0.443748	0.615853	0.593524
C-A	0.894940	0.965678	0.938393	0.705771	0.915770
D-A	0.292990	0.819273	0.840159	0.433962	0.170064
E-A	0.292990	0.987142	0.611546	0.978983	0.973180
base-A	0.999639	0.428473	0.526624	0.999722	0.949847
C-B	0.003110	0.910009	0.938393	0.999991	0.990722
D-B	0.973442	0.699014	0.985458	0.999722	0.973180
E-B	0.973442	0.998061	0.999815	0.954044	0.958747
base-B	0.027991	0.563215	0.999994	0.788278	0.130146
D-C	0.027991	0.998061	0.999815	0.998017	0.746388
E-C	0.027991	0.699014	0.985458	0.978983	0.999887
base-C	0.973442	0.096515	0.967604	0.858851	0.410626
E-D	1.000000	0.428473	0.998667	0.858851	0.593524
base-D	0.166905	0.033901	0.994775	0.615853	0.016084
base-E	0.166905	0.819273	0.999994	0.998017	0.566884

analysis: although one can rank the strategies accordingly to the metalevel accuracy, the results show that their impact on the baselevel is lower than expected.

- There is a trade-off between accuracy and computational time. The most accurate strategies has a processing time up to one thousand times lower than the time required for the fastest strategy. However, the performance in these cases is not optimal. It will be up to the practitioner to decide which one to use.

In order to validate the observations, statistical significance tests were performed. Most validations are calculated with ANOVA (to understand if there are differences in the populations studied in each observation) and Tukey's honest significant difference tests (to understand whether the differences are statistical significant or not). Table 4 presents the results of the Tukey's test for the following null hypothesis: there is no difference in performance among baseline (base), average performance of all algorithms (avg) and average performance of the top 3 algorithms (top3) for each metatarget and on a general point of view. The *p*-values are highlighted if the differences are significant, i.e. *p*-value < 0.05. One can assert that the average of the top 3 algorithms are indeed better than the baseline. The results also show that the only metatarget for which the average of all algorithms is statistical significantly better than the baseline is NDCG. The variance in the results for the other metatargets make it impossible to make such assertion for those cases. However, on the analysis for all metatargets, the difference remains statistically significant. It is also possible to conclude that the average top 3 is better than average of all algorithms for the NDCG, NMAE and RMSE metatargets and also on a global point of view.

In order to validate the statistical significance in the ranking of strategies, the previous tests, but with the results aggregated by strategy, can be performed. The comparisons are made for each metatarget and also for the combination of all metatargets. The *p*-values for the pairwise comparison using Tukey's test are presented in Table 5. The results show that the observations regarding the ranking of strategies do not hold statistical significance, except for few special cases. In fact, when considering all metatargets, the only statistically significant difference is that strategy D is better than the baseline. All other comparisons in the set of all metatargets do not hold any statistical significant value. This trend extends when the comparison is made for each metatarget, with the exception of AUC. Here, there is evidence to support that B is better than the baseline and that C is worse than B, D and E. In the NDCG metatarget, D is also shown to be better than the baseline.

The statistical significance of multiple algorithms on multiple datasets can be verified using Critical Difference (CD) diagrams [11]. This consists of plotting the average ranking position for each element being compared and calculate the CD interval that states that there is no evidence in the data to show that the elements within that interval can be considered different. In CD plots, two elements not connected by a line can be considered different, i.e., one algorithm is ranked higher than the other. In this work, the datasets are provided by the combinations of metafeature strategies and metatargets, which refer to the independent and dependent variables, respectively.

The CD diagram in Fig. 10 allows to confirm that SVM polynomial is the highest ranked algorithm. However, there are no statistically significant differences among SVM polynomial, SVM radial, C4.5, KNN and SVM linear. Despite this, one can

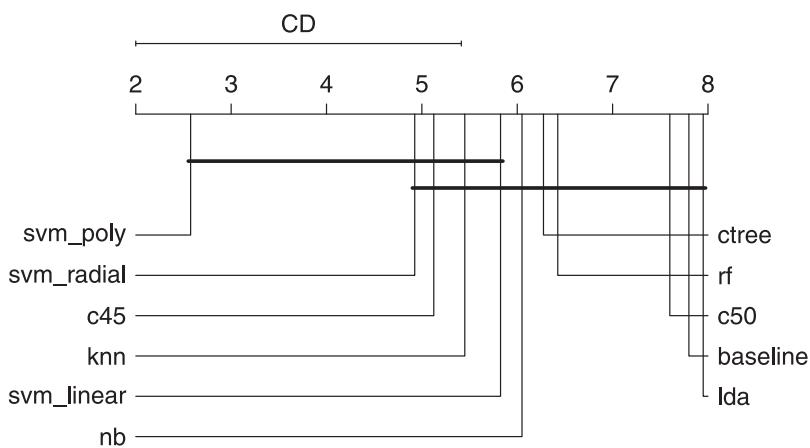


Fig. 10. CD diagrams for meta-algorithms across strategies and metatargets.

assert that SVM polynomial is better than Naive Bayes, ctree, random forest, C5.0, LDA and the baseline majority voting. In terms of statistical significance, no other conclusions can be drawn from this diagram.

6. Conclusions

This work analyzes in depth the problem of algorithm selection for Recommender Systems, with focus on Collaborative Filtering. It starts with a systematic literature review regarding related work. In this review, the problem is framed within the classical Metalearning conceptual framework and each of the available works is presented and discussed on the several dimensions of the problem. Afterwards, an empirical study is performed to assess the quality of a subset of the approaches discussed on the selection of algorithms. Experimental results regarding the metalevel accuracy, baselevel impact and computational resources are presented, discussed and statistically validated.

The literature review shows that most work is performed on Collaborative Filtering, with a reduced number of datasets, algorithms and evaluation measures in the base-level. However, recent works have improved such dimensions, effectively contributing to advances in the field. In terms of meta-level, there are several approaches which look at the algorithm selection problem in different and valid perspectives. Most works used regression approaches with a wide range of metafeatures. However, there was no comparison among them, which prevents the understanding of their merits.

To solve this problem, we conducted an empirical study. It has shown that, in the best case scenarios, all strategies are able to create effective models to solve the algorithm selection problem. However, in a deeper look, all strategies have different behaviors depending on the metatargets and meta-algorithms used, which indicates that the research problem is not yet solved. The results have also shown that strategy D is statistically significantly better than the baseline, although the same conclusions cannot be drawn regarding the other strategies. The main conclusion of this study lies in the fact that there is no single best strategy that always outperforms the others, but rather aspects on which the performance is better. The authors highlighted the advantages and weaknesses of each work, but leave the choice of metafeature strategy to the practitioner. Nevertheless, the knowledge gathered in this document allows to positively direct future work in this research topic.

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Motivation and metacognition when learning a complex system

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Our cognitive-motivational process model (Vollmeyer & Rheinberg, 1998) assumes that motivational factors (i.e., mastery confidence, incompetence fear, interest, and challenge) affect performance via mediators. Previous studies (Vollmeyer, Rollett, & Rheinberg, 1997) found that strategy systematicity and motivational state during learning mediate the impact of initial motivation on the learning of a complex system. Potential mediators could be other cognitive (e.g., hypothesis testing) and metacognitive aspects, in that more motivated learners (high mastery confidence, low incompetence fear, high interest) analyse more deeply. Verbal protocols from 44 students who learnt to control a complex dynamic system were collected. We measured their initial motivation (on the four factors specified), then during learning we assessed their strategy systematicity and motivational state. Additionally, we analysed the verbal protocols to obtain indicators of learners' cognitive and metacognitive processes. Performance measures were levels of knowledge acquisition and application. The cognitive-motivational process model was replicated. Qualitative cognitive aspects were added as mediators, however, the results for metacognition were problematic, partly because participants gave relatively few clearly expressed metacognitive statements.

Motivation, metacognition, and learning

When trying to understand a text, a mathematical problem, or a new computer game, many different processes are involved. Not only are cognitive processes important, so are metacognitive, motivational, and emotional processes. The aim of our research is to disentangle these different processes and to show how it is possible to simultaneously measure each of these processes. Whereas researchers have mainly studied a single process at a time, recently some have tried to address how these processes may interact: for example, Boekaerts's (1996) work on *self-regulated learning*, Efklides, Papadaki, Papantonio, and Kiosseoglou's (1997) study on *metacognitive experience*, and our own *cognitive-motivational*

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model (Vollmeyer & Rheinberg, 1998). The broadest of these concepts is metacognitive experience as defined by Flavell (1979). It includes all conscious emotional and cognitive feelings which arise while undertaking cognitive activities. These could be, for example, the feeling that it is impossible to understand the task, or the feeling that one is close to the goal. However, the term metacognition does not embrace just metacognitive experience, but overlaps with the concept of motivation. To emphasise that metacognition has a broad meaning, Weinert (1984, p. 17) showed that variables used to measure both metacognition and motivation are sometimes defined and operationalised the same way (e.g., evaluation of task difficulty, or evaluation of learning results).

How does our own cognitive-motivational model relate to metacognitive experience? In our model we assumed that initial motivation – consisting of task-specific *mastery confidence*, *incompetence fear*, *challenge*, and *interest* – helped knowledge acquisition via two mediating variables: *strategy systematicity* and *motivational state* during learning. Whereas strategy systematicity is a cognitive process variable indicating how systematically participants explore the material, motivational state monitors aspects of their motivational process such as how much fun participants have during the learning task, and their confidence in finding the correct solution. This confidence relates to what participants feel during learning, and is part of what has been studied under the label metacognitive experience. Previous empirical studies (Vollmeyer, Rollett, & Rheinberg, 1997, 1998) showed that participants who were more confident and had less fear chose more systematic strategies, and had a more positive motivational state (i.e., had more fun and were more confident during learning). Both of these mediator variables led to more knowledge acquisition. When participants had to apply their acquired knowledge, again the motivational state was associated with higher performance.

The two mediating variables – strategy systematicity and motivational state – allowed us to coherently explain the learning process. In particular, we could show that motivational processes affected cognitive processes, and that cognitive processes themselves influenced the motivational state during learning. In our previous studies we have used only strategy systematicity to access learners' cognitive processes. Under strategy systematicity we understand how well-directed learners explore a task. However, strategy systematicity is only a weak measure of specific cognitive processes because other factors, such as motivation, ability, or simple luck may influence which strategy is chosen. In particular, to analyse the learning process we need to take into account that different learners can represent the task in different ways, that is, they may have different models of the task (Burns & Vollmeyer, 1997). Their model will influence the cognitive aspects of the learning process, for example, what sorts of hypotheses they form and test. The model will also influence metacognitive aspects of learning. For example, if the task is evaluated as unfamiliar then a different plan will be necessary than for a familiar task.

To measure such *cognitive aspects*, we examined people's hypothesis testing, including their expectations based on their model of the task. Previously, we have used strategy systematicity as an indirect measure of which hypotheses were tested. In this study, we wanted to have direct indicators for what kind of hypotheses participants tested. Depending on these hypotheses, participants should analyse the results in different ways. When participants have to apply their knowledge, they also have to decide on a strategy. Those who have more knowledge should choose more effective strategies. In a study, Vollmeyer and Burns (1995) used the thinking-aloud technique (Ericsson & Simon, 1993), and found evidence that when learners had detailed hypotheses their knowledge acquisition was superior. Therefore, this technique was used in the following experiment.

The second set of variables we wanted to add to our model was *metacognition*. Especially in difficult and complex tasks such as ours, it should be an advantage not only to use one's cognitive abilities but also to use abilities that have been studied under the topic of metacognition. To operationalise metacognition we followed Simon's (1996) idea, that metacognition is mainly used for executive control (i.e., behaviour, strategy, or program that marshals and controls cognitive resources for performance of a task, see Simon, 1979, p. 42). An important function of executive control pointed out by Simon is planning, a metacognitive aspect of problem solving emphasised by Davidson, Deuser, and Sternberg (1994). Therefore,

when analysing the verbal protocols generated by the thinking-aloud technique, we categorised remarks indicating that participants planned their learning as metacognition.

Another interesting question we explored was which emotions do participants experience while doing our learning task and whether these emotions are expressed well enough to be consistently revealed in verbal protocols. The study of emotions during learning is important, as it has been found that people's mood can affect learning though the effects may vary with the task (for a summary, see Bless, 1997). However, emotions have not been studied using extended complex tasks as emotions tend to be short lasting (Abele, 1995). Therefore, we examined the verbal protocols for emotional remarks, especially those showing reactions to success and failure. If this method proves reliable and we find sufficient volume of emotional remarks, this would enable us to use the data to test hypotheses about emotions and learning.

Therefore, the aim of the following study was to extend and elaborate our cognitive-motivational model. More direct measures of cognitive aspects of learning should enable us to explain what leads to systematic strategies. People producing more detailed hypotheses should use more systematic strategies, which in turn should help learners to analyse the results in a more effective way. Metacognitive aspects were expected to work in parallel with the cognitive ones, as both have their origin in participants' model of the task: Those who have a clearer understanding of what the task is about should report more cognitive and metacognitive thoughts in their protocols. In addition, this study allowed us to replicate our cognitive-motivational process model, in which initial motivation affects learning via motivational and cognitive mediators.

Our learning task: The biology-lab

As in Vollmeyer, Burns, and Holyoak (1996) and Vollmeyer et al. (1997, 1998), we used the system biology-lab. It is a computer-driven system that was constructed with the shell DYNAMIS (Funke, 1991). The cover story we told our participants was that they were in a lab in which the effects of three medicines (A, B, C) on three substances found in the body (Thyroxin, Histamine, Serotonin) were to be tested. The structure of the system, illustrated in Figure 1, was such that one output was relatively simple to manipulate because it was influenced by only one input (Medicine A → Serotonin). The other two outputs were more complex, because each was influenced by two factors. One output (Thyroxin) was affected by two inputs, and the other (Histamine) is affected by a decay factor (marked as a circle connected to the output) in addition to a single input variable. The decay factor was implemented by subtracting a percentage of the output's previous value on each trial. Decay was a dynamic aspect of the system, because it yielded state changes even if there was no input (i.e., all inputs were set to zero). The system was thus complex in that it involved multiple input variables that had to be manipulated in order to control multiple output variables, and dynamic in that the state of the system changed as a joint function of external inputs and internal decay.

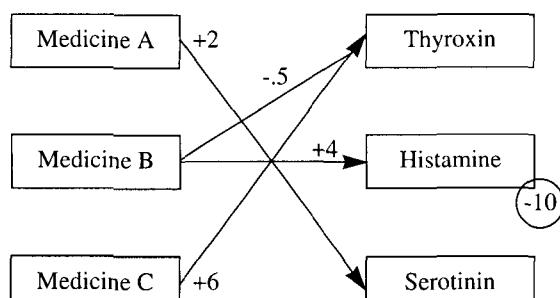


Figure 1. Structure of the biology-lab system

This system can be used for studying two phases: first, participants have to acquire knowledge, that is how the input variables are connected to the output variables (learning phase); second, participants have to apply their knowledge in that they have to reach goal values for each output variable (application phase). For each phase, we calculated a performance measure: For the learning phase, we calculated how much participants learnt about the system's links, for the application phase how close they got to the goal states.

Ecological validity of the task. Using an artificial learning task in a laboratory allowed us greater control of learning, but it is clearly a different task to the complex environment of the classroom. However, our focus was on the process by which motivation and cognition interact, and there is no reason to expect this process to differ between environments, regardless of how complex are the factors affecting motivation and cognition. The critical issue is whether we adequately measured and sampled the range of values for our motivational and cognitive variables. Biology-lab appears to do this, as previous studies have found that participants find it challenging (in this study on a seven-point scale [1=low challenge, 7=high challenge], $M=4.85$, $SD=.91$), use a variety of strategies, and find the task difficult (only some reach the goal states). We will return to the issue of generalisability in the discussion.

Method

Participants

Forty-four university psychology students and high school students in Potsdam participated in the study, for which they received DM 25 each.

Procedure

Before explaining the biology-lab task, we told participants that it was very important for us to learn about what they are thinking during the experiment. Therefore, they should talk aloud while working with the system. When doing verbal protocols, Ericsson and Simon (1993, p. 376) recommended a short exercise, which is multiplying 24 times 34 while talking aloud. To practise talking aloud, we had participants do this exercise. Then they read a description of the task.

Vollmeyer et al. (1996) showed that a good strategy for learning about the system was to vary only one input variable at a time, which is our high systematicity category. This strategy was also described in Bandura and Wood (1989), and Putz-Osterloh (1993). We explained this strategy to all participants in order to reduce the variance of their performance. After the instructions, they filled out the QCM (Questionnaire on Current Motivation, Vollmeyer & Rheinberg, 1998) measuring their initial motivation on the four factors: *mastery confidence*, *incompetence fear*, *interest*, and *challenge*. Then they started manipulating the inputs of the system to try to induce the underlying structure shown in Figure 1. While working with the system they were allowed to take as many notes as they wanted as well as use a calculator.

After each of the three learning rounds participants filled out the structure diagram (see below) and answered the motivational state questionnaire. When the learning phase was finished, participants were asked to reach the goal states which were Thyroxin on 700, Histamine on 900, and Serotonin on 50. The experiment took about two hours.

Verbal protocols

Ericsson and Simon (1993) described how verbal protocols should be used. They concluded that concurrent verbalisations while learning have positive effects on learning because explicitly formulating rules helps knowledge acquisition. However, participants who had to verbalise took more time to finish the task (Deffner, 1984). In addition, when the task is difficult, participants stopped talking (Ericsson & Simon, 1993). Therefore, this method creates a lot of missing data in difficult tasks as participants stop talking aloud. Ericsson and

Simon recommended that as soon as participants become silent, they should be asked to continue talking. However, motivation could be reduced if the experimenter interrupted the learning process too often. Given that we are interested in motivation, we decided not to follow this recommendation completely, but to remind participants only at certain times. Otherwise the experimenter was not in the room.

Measures

Initial motivation. With the QCM, we measured the motivational factors challenge (e.g., "This task is a real challenge for me"), "If I can do this task, I will feel proud of myself"), mastery confidence (e.g., "I think everyone could do this task", "I think I am up to the difficulty of the task"), incompetence fear (e.g., "I'm a little bit worried", "I'm afraid I will make a fool out of myself") and interest (e.g., "After having read the instructions, the task seems to be very interesting", "I would work on this task even in my free time").

Mediating variables. Seven mediating variables were measured in order to investigate the process linking initial motivation to the learning outcomes: (1) strategy systematicity, (2) motivational state, (3) hypothesis testing, (4) analysis of results, (5) strategy for reaching the goal states, (6) metacognition, and (7) emotional reflection. The last five of these variables were coded from the participants' verbal protocols.

Mediator 1: Strategy systematicity. To measure how systematically participants explored the system, we categorised each of the 18 trials into one out of the following three categories.

High systematicity was assigned when one input was varied, and the other two were kept constant. For example, a participant entered 10 for Medicine A, 0 for Medicine B, 0 for Medicine C. This strategy allowed participants to discover the system's structure, as they can observe which outputs a single varied input variable changed in the system. We recommended this strategy to the participants at the beginning of the study.

Medium systematicity was assigned when multiple inputs were varied, but a systematicity could be recognised. For example, a participant entered 100 for Medicine A, 10 for Medicine B, 10 for Medicine C; or, 100 for Medicine A, 100 for Medicine B, -100 for Medicine C.

Low systematicity was assigned when a useful systematicity could not be recognised. For example, a participant varied each input by the same amount (e.g., 10 for Medicine A, 10 for Medicine B, 10 for Medicine C). This is systematic, but futile, because it can not help with learning about the structure.

The categories for strategy systematicity as well as categories for the verbal protocols were coded by multiple raters. To check interrater reliability, 180 trials were coded by two raters and we calculated reliability with Cohen's κ (Cohen, 1960). For all other trials, strategy and protocols were coded by only one rater.

For the strategy systematicity we received a Cohen's $\kappa=.94$. To calculate a strategy systematicity score, we ranked a trial's systematicity from one to three, with a value of three indicating a high systematic strategy for a trial, and one a low systematic strategy. Then we averaged the six trials per round to derive a systematicity value for each round.

Mediator 2: Motivational state. At the end of every learning round, participants answered seven questions on a seven-point scale which measured the positive valence and ease of concentration ("The task is fun", "I have no difficulties concentrating on the task", "I think the task needs a lot of effort", "I would love to stop working on the task") and self-efficacy ("I'm sure I will find the correct solution", "It's clear to me how to continue", "I think I won't master the task"). The self-efficacy items were similar to those used in studies by Bandura and Wood (1989), Cervone, Jiwani, and Wood (1991), and Schoppe (1997). These items were averaged as they were homogenous (Round 1, Cronbach's $\alpha=.90$; Rounds 2 and 3, Cronbach's $\alpha=.91$). In an earlier study (Vollmeyer, Rollett, & Rheinberg, 1997) we used only three out of the seven items, however, the three and seven items are highly correlated (Round 1, $r=.95$; Rounds 2 and 3, $r=.96$).

Mediators 3-7: Verbal protocols. We wanted to investigate how participants are thinking and feeling while exploring the system. To do so, we coded their verbal protocols for

metacognition, emotional reflections, and the cognitive aspects: hypothesis testing, analysis of results, strategy for reaching the goal states.

Hypothesis testing indicated what level of hypotheses a participant formulated before entering numbers for the input variables. The categories were: *no hypothesis testing* (i.e., participants did not say which hypothesis they had), *nonpredictive* (e.g., “Let’s see what happens if I change Medicine A.”), *testing links* (e.g., “I will try whether Medicine A has an effect on Serotonin.”), *testing directions or weights* (e.g., “Perhaps Medicine A affects Serotonin with +2.”). Two raters had an agreement of $\kappa=.79$. As we assumed that testing directions and weights is the most informative way to test hypotheses in this system whereas having no hypothesis is the least informative, we ranked this variable from one to four. A value of one indicated no hypothesis testing, and a value of four indicated testing of directions and weights. These ranks were averaged over the six trials of each round to yield an hypothesis testing score.

After each input participants analysed the changes in the output variables, which we refer to as *analysis of results*. The categories were: *no analysis* (participants did not say whether or how they analysed the results), *simple analysis* (e.g., “Why did Serotonin change?”), *organised analysis* (e.g., rule induction from relating changes to their effects), *summarising* (e.g., “That’s what I know now, I still have to learn...”). For these categories, two raters had an agreement of $\kappa=.77$. We also assumed a hierarchy for this variable. The category no analysis was given a rank of one and summarising a rank of four. Again we averaged these ranks across the six trials of each learning round.

The *strategy for reaching the goal states* was coded as: *no strategy* (i.e., participants did not say how they tried to reach the goal states), *trial and error* (e.g., “Let’s give in a 10.”), *pushing* (e.g., “The difference to the goal state is 20, so let’s add something to Medicine A.”), *calculating* (e.g., “If the difference to the goal state of Serotonin is 100 then I have to add 50 to Medicine A.”). For this variable, two raters had an agreement of $\kappa=.76$. As having no strategy should be least effective and calculating the most, we ranked the categories from one (no strategy) to four (calculating) and averaged the ranks across the six trials of each learning round.

For *metacognition* we had two categories: *planning* (e.g., “What do I do next? What is necessary?”), and *self control* (e.g., “I have to concentrate more”).

Emotional reflection was recorded with the categories: *failure* (e.g., “... and I thought Serotonin would increase.”), *confusion* (e.g., “I don’t know what to do next.”), and *success* (e.g., “Exactly what I expected.”).

Dependent variables. We measured performance for the learning phase (structure score) as well as for the application phase (goal achievement).

(1) *Structure score* (acquired knowledge). After each round of the learning phase, participants had to complete a diagram, similar to the one in Figure 1 but with all links and weights omitted. Using this diagram they had to indicate their knowledge about the system’s structure by drawing a link between an input and an output, if they noticed a relationship. Each link could be given a direction (+/-) and a weight, if participants thought they knew how strong the impact was. To indicate that an output had a decay participants could write a weight into the empty circle attached to an output.

The structure score consisted of (1) the number of correct links between the inputs and the outputs, (2) the number of correct directions (+/-), and (3) the number of correct weights. The sums for the correct links and the correct directions were corrected for guessing, in that the number of correct entries (hits) was divided by the maximum number of correct hits (see Woodworth & Schlosberg, 1954, p. 700). This structure score varied between 3.0 (best value) and a theoretical minimum of -1.8. (It was negative if participants incorrectly guessed too much.)

(2) *Goal achievement.* Goal achievement in reaching the goal state during application phase was computed as the sum of the absolute differences between the target and the obtained number for each of the three output variables. As this measure produced a skewed distribution, the variance was corrected by applying a logarithmic transformation (\ln). Goal achievement was computed for each of the six trials that comprised each round in the application phase, in order to determine how participants were able to approach the target

goal. As there was no difference in performance between trials, the mean error for the six trials was used. However, this meant that high scores were indicators of poor performance. So that all performance measures would be in the same direction, we subtracted all these scores from an arbitrary constant.

Results

After the first round of the learning phase, five participants said they knew everything about the system and wanted to see the goal states. A further five participants wanted to start the application round after the second round. Thus, we analysed protocols from 44, 39, and 34 participants in Round 1, Round 2, and Round 3, respectively. The application round was completed by all 44 participants.

Verbal protocols

One aim of the study was to investigate whether the thinking aloud method could provide additional information about the effect of motivational factors on learning, especially with regard to cognitive and metacognitive aspects. First, we checked whether participants kept talking aloud throughout the learning rounds. Table 1 shows that the number of classifiable trials declined over the learning rounds. For example, the percentage of trials on which no hypothesis was formulated aloud increased from 22% in Round 1 to 63% in Round 3. Similarly, there was a decline in trials classifiable on analysis of results. This suggests that verbal protocols may not give a full picture of the learning processes. That verbalisations may hinder insight was shown by Schooler, Ohlsson, and Brooks (1993). Dominowski (1998) provides an overview on the pros and cons on verbalisation and problem solving.

Table 1

Verbal protocols: Number of trials classified into each category for each round, together with that number as a percentage of the total number of trials. Total number of trials in a round is the number of participants multiplied by six

Total trials	Round 1 264 (100%)	Round 2 234 (100%)	Round 3 204 (100%)	Round 4 264 (100%)
<i>hypothesis testing:</i>				
- no hypothesis testing	59 (22%)	109 (47%)	129 (63%)	
- nonpredictive	136 (52%)	50 (21%)	26 (13%)	
- links	43 (16%)	36 (15%)	31 (15%)	
- directions, weights	26 (10%)	39 (17%)	18 (9%)	
<i>analysis of results:</i>				
- no analysis	64 (24%)	99 (42%)	120 (59%)	
- simple	14 (6%)	4 (2%)	12 (6%)	
- organised	135 (51%)	89 (38%)	49 (24%)	
- summarising	51 (19%)	42 (18%)	23 (11%)	
<i>strategy for reaching goal:</i>				
- no strategy				84 (32%)
- trial and error				23 (9%)
- pushing				55 (21%)
- calculating				102 (38%)
<i>metacognition:</i>				
- no metacognition	256 (97%)	212 (91%)	197 (97%)	
- planning	8 (3%)	21 (9%)	7 (3%)	
- self-control	0 (0%)	1 (0%)	0 (0%)	
<i>emotional reflection:</i>				
- no emotional reflections	247 (94%)	200 (85%)	184 (90%)	187 (71%)
- failure	6 (2%)	11 (5%)	10 (5%)	52 (20%)
- surprise, confusion	7 (3%)	19 (8%)	4 (2%)	11 (4%)
- success	4 (1%)	4 (2%)	6 (3%)	14 (5%)

Another problem we noticed was that participants verbalised few emotional reflections or metacognition (see Table 1). In the learning phase, most of the trials could be categorised as non-emotional. However, in the application phase there was a greater number of trials for which expressions of failure were coded (20%). Therefore, we could successfully classify participants as expressing failure, at a time they were likely to be confronted with it (i.e., when they must reach a difficult goal state). Metacognition was also difficult to analyse because there were few instances. During learning very few participants stated their plans or said how they controlled their learning. For these two metacognitive variables there were too few instances to analyse them with regard to initial motivation or performance. In the application phase, participants talked aloud more. Only in 32% of the trials did participants not say which strategy they used for trying to reach the goal states.

In summary, we had three protocol variables with enough instances to enable us to study their relationship to motivation and performance. All of these were measures of cognitive aspects: hypothesis testing, analysis of results, strategy for reaching goal.

Influence of initial motivation (QCM) on hypothesis testing and analysis of results

For this analysis the data is missing for one participant who did not fill out the QCM. The hypothesis was that participants who have high scores on interest, perceive high challenge, high mastery competence, or low incompetence fear should have been more effective at hypothesis testing and at analysis of results. This was because we expected them to think deeply about the system. Therefore, we correlated the initial motivational factors with the two analysable variables which were extracted from the verbal protocols in the learning rounds. Effective hypothesis testing could not be predicted by either challenge (for Rounds 1 to 3, $p's > .60$), or mastery competence (for Rounds 1 to 3, $p's > .20$). A pattern in the right direction, but not significant, could be found in that more interested participants had more effective hypothesis testing and participants with less incompetence fear had more detailed hypotheses. The effects of initial motivation were also small for analysis of results: For none of the three rounds we did find effects of challenge ($p's > .20$), mastery competence ($p's > .40$), or interest ($p's > .20$). Only incompetence fear showed the expected, but not significant pattern, in that participants with high fear were worse at analysing the results.

Influence of hypothesis testing and analysis of results on the learning process

In the learning phase, we measured the two mediating variables, strategy systematicity and the motivational state, as well as the performance (structure score). As hypothesis testing and analysis of results are new variables in our model we report their correlations with the above stated variables (see Table 2). Participants with more systematic strategies tested hypotheses more effectively and analysed the results more carefully over all three rounds. When participants were testing hypotheses more effectively, they had more fun and were more sure that they would learn the system (i.e., had more positive motivational state) than with less effective hypothesis testing. This effect was not true for analysis of results for which all correlations turned out to be not significant ($p's > .12$). A higher structure score was obtained when hypothesis testing and analysis of results were more sophisticated.

In sum, two cognitive variables from the verbal protocols correlated with the learning process in that hypothesis testing was associated with motivational (motivational state) and cognitive variables (strategy systematicity, structure score) but analysis of results was associated only with the cognitive ones.

Table 2

Correlations between hypothesis testing, analysis of results and strategy systematicity, motivational state, structure score

correlation between:	Round 1 N=44		Round 2 N=39		Round 3 N=34	
	r	p	r	p	r	p
hypothesis testing and strategy systematicity	.43	.003	.31	.061	.30	.100
hypothesis testing and motivational state	.41	.005	.29	.075	.26	.150
hypothesis testing and structure score	.33	.029	.45	.004	.39	.023
analysis of results and strategy systematicity	.37	.013	.26	.110	.25	.170
analysis of results and motivational state	.24	.120	.18	.290	.06	.720
analysis of results and structure score	.41	.006	.43	.007	.04	.840

Influence of application round strategy

Those participants who chose a better strategy in the application round, which was one of the three cognitive aspects, had more fun and were more sure about learning the system (i.e., motivational state), $r(44)=.31$, $p=.045$, and had more knowledge about the system, $r(44)=.49$, $p=.001$, at the end of their last learning round. Choosing a better strategy helped participants come closer to the goal state, $r(44)=.32$, $p=.032$.

The cognitive-motivational process model

Consistent with our cognitive-motivational model, we tested the predictions that initial motivation (mastery competence, incompetence fear) would influence performance via the mediating variables of strategy systematicity and motivational state. To analyse this process, the appropriate statistical analysis is a path analysis. Ideally, the new mediators measured from the verbal protocols should be added into the model. Unlike our previous study (Vollmeyer et al., 1997), ten participants finished before the third round. Therefore, we analysed the individual last round that each participant completed (i.e., for those who finished in the first round we analysed Round 1, for those who finished in the second round Round 2, etc.). Thus in the present study we lost the information showing how variables develop and interact over the learning rounds. To our previous model, we added the cognitive aspects (hypothesis testing, analysis of results, and strategy for reaching the goal) and calculated a structural equation model using Bentler's (1992) program. The result can be seen in Figure 2. Fitting the theoretically derived model to the data gave a high model fit, $CFI=0.98$, $\chi^2(19)=21.50$, $p>.31$.

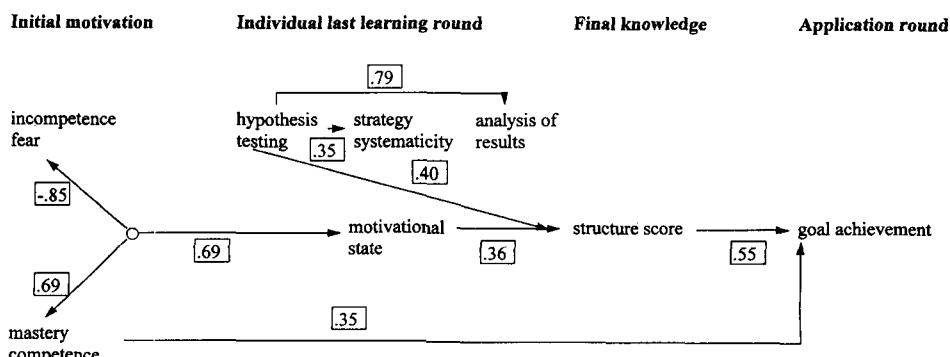


Figure 2. Path analysis for the cognitive-motivational process model

As incompetence fear and mastery competence are highly correlated, $r(44)=-.59, p=.001$, we combined them into a latent variable as we did previously (Vollmeyer et al., 1997). This initial motivation affected motivation during learning. As a good strategy was explained before working with the task, almost all participants followed our instruction on the first three trials of Round 1 (trial 1: 96%, trial 2: 96%, trial 3: 98%). As there is only a small variance we did not expect strategy to be affected by initial motivation. However, having a detailed hypothesis should increase persistence with a more systematic strategy, and assist with analysing the results more carefully. The model in Figure 2 shows, that these assumptions were confirmed. Having a more detailed hypothesis and a more positive motivational state (i.e., more fun, and a higher expectation of learning the system) led to more knowledge about the system's structure (structure score). This knowledge was helpful for reaching the goal state. Unlike in our previous study (Vollmeyer et al., 1997), it was not the motivational state during learning which was associated with goal achievement. In the present study, initial mastery competence directly affected how well the goal states were reached. Beside these differences across studies, there are also differences between what is shown by the individual correlations and by the path analysis. First, although the strategy for reaching the goal states was correlated with the mediating and performance variables, the variance in the model was better explained with other variables. Second, the same was true for interest. Interest correlated with mediating and performance variables, however, the latent variable explained more variance in the model.

Discussion

The aim of this study was to integrate variables for the qualitative cognitive and metacognitive aspects of learning into our cognitive-motivational model. To do so, we first had to test whether we could replicate our empirical model. The replication was partially successful. In addition, we could integrate the new cognitive aspects, but not the metacognitive ones. As in our previous studies (Vollmeyer et al., 1997, 1998), the path-analysis showed that initial motivation (incompetence fear and mastery competence) affected knowledge acquisition through motivational state. However, there were also differences: (1) Strategy systematicity did not affect knowledge acquisition (but hypothesis testing did). (2) Motivational state during learning did not affect strategy systematicity. (3) Motivational state had no effect on the performance in the application round (but initial motivation did).

Verbal protocols

Deviations from our previous model may be partially due to the fact that different learners completed different number of rounds. Therefore, we restricted our analysis to the individual last learning round which may have led to a loss of relevant process characteristics that we found in our previous path-analyses.

The deviations could also be explained as due to the use of the thinking-aloud technique, which we added in order to measure cognitive and metacognitive aspects. It is possible that this technique created an environment in which participants thought more deeply, as they were forced to verbalise their thoughts, which in turn would emphasise the cognitive aspects of the task. This could be the reason why hypothesis testing had such a central position (it was linked to systematicity, analysis of results, knowledge acquisition) in the learning process. The emphasis on cognitive aspects may also be responsible for the finding that the motivational state affected knowledge acquisition, but not its application (for which mastery confidence was a better predictor).

Apart from the possibility that the thinking-aloud technique may have emphasised the cognitive aspects of the task, there was a more serious problem with applying this technique to this task: We lost a lot of data because participants stopped talking aloud. Participants also

complained that verbalising their thoughts was strange for them. Therefore, data on verbal protocols had a selective bias in this experiment, that only those who were verbalising, revealed the true values of the variables we used to measure the learning process. The fact that participants did not like thinking aloud may have hindered them from expressing their emotions or describing how they controlled their learning.

Metacognition – Metacognitive experience

What does our study say about metacognition or metacognitive experience? Unfortunately, the verbal protocols did not reveal how participants planned and controlled their learning. Using verbal protocols for studying the effects of metacognition on learning, may require continually reminding participants to talk aloud. However, this intervention could be detrimental to motivation. Whether this means that this is a fundamental limitation to studying motivation and metacognitive processes, is a question for further studies.

Our modelling showed the importance of process variables recorded during learning. Given that metacognitive experience overlaps with motivational state (e.g., both measure expectancy of learning the system among other measures), this suggests that in order to understand the relationship of metacognitive experience to learning, an emphasis should be put on measures during learning.

Future research

Up to now our results have been validated for only a single laboratory task. This limits our conclusions to situations in which people have to induce rules from observations presented on a computer. However, as multimedia learning gains importance, a next step will be to transfer.

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Notre modèle de processus cognitivo-motivationnel (Vollmeyer & Rheinberg, 1998), suppose que les facteurs motivationnels (i.e., confiance dans sa maîtrise, crainte de l'incompétence, intérêt, et défi) affectent la performance par l'intermédiaire de médiateurs. Des études antérieures (Vollmeyer, Rollett, & Rheinberg, 1997) ont montré que la systématique de la stratégie et l'état motivationnel pendant l'apprentissage d'un système complexe. Les médiateurs potentiels peuvent concerner d'autres aspects cognitifs et métacognitifs, étant donné que les apprenants les plus motivés (niveau élevé de confiance dans sa maîtrise, faible crainte de son incompétence, niveau élevé d'intérêt) analysent plus profondément. On a recueilli les protocoles verbaux de 44 étudiants qui apprenaient à contrôler un système

dynamique complexe. On a mesuré leur motivation initiale (sur les quatre facteurs spécifiés) puis, durant l'apprentissage, on a évalué leur systématicité stratégique et leur état motivationnel. En plus, on a analysé les protocoles verbaux afin d'obtenir des indicateurs de processus cognitifs et métacognitifs d'apprentisage. Les mesures de performance utilisées ont été des niveaux d'acquisition et d'application de connaissances. On a alors répliqué le modèle de processus cognitivo-motivationnel à ces données. Les aspects cognitifs qualitatifs ont été introduits, en plus, comme médiateurs, mais les résultats relatifs à la métacognition ont été problématiques du fait, en partie, que les participants ont fourni relativement peu d'énoncés méta-cognitifs exprimés clairement.

Key words: Complex system, Metacognition, Motivation.

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Current theme of research:

Motivation and learning, problem solving.

Most relevant publications in the field of Psychology of Education:

- Vollmeyer, R., Burns, B.D., & Holyoak, K.J. (1996). The impact of goal on strategy use and the acquisition of problem structure. *Cognitive Science*, 20, 75-100.
- Vollmeyer, R., Rollett, W., & Rheinberg, F. (1997). How motivation affects learning. In M.G. Shaffo & P. Langley (Eds.), *Proceedings of the Nineteenth Annual Conference of the Cognitive Science Society* (pp. 796-801). Hillsdale, NJ: Erlbaum.
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Current theme of research:

Incentives of learning activities, motive modification training, motivation and learning.

Most relevant publications in the field of Psychology of Education:

- Rheinberg, F. (1996). Von der Lernmotivation zur Lernleistung. Was liegt dazwischen? [From motivation to learn to learning outcome. What's between?]. In J. Möller & O. Köller (Eds.), *Emotion, Kognition und Schulleistung / Emotion, cognition, and academic achievement* (pp. 23-51). Weinheim: PVU.

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Open Problems in Recommender Systems

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Abstract—With increasing information available online, requirement for accurate information filtering tools/ information retrieval have become necessary. Recommender systems have been a crucial research subject after the inclusion of the very first paper on filtering. Recommender Systems is a tool that provides recommendations for products/services which maybe of liking to a particular consumer. Despite the fact that research on recommender systems has extended extensively over the last decades, there's still requirement in the complete literature evaluation of the research made till date and classification of Recommender Systems. This paper presents a categorical review and provides a survey on the diversity & techniques of Recommender systems. The open problems in the area are pinpointed and mapped to the respective recommendation paradigm type thus giving an insight to the research trends in the field of recommender system. The intent of this work is to serve as a base literature review to beginners and at the same time aid as an important pertinent survey for identifying the opportunities in the area.

Keywords—Recommender Systems; Types; Issues

I. INTRODUCTION

The improvement in Information Technology has increased the inflow of products in every domain via E-market by many folds. Although it's easier for a consumer to choose from small set items but when the item set increases, it is cumbersome and difficult for user to consider various properties of alternate product. Following these conditions, user wants recommendations from the known users who have information regarding the product. We currently live in an era where there is overload of information. We are surrounded by a plethora of information in the form of papers, reviews, blogs and comments on various social networking websites. The number of people who use the Internet witnessed the increase of approximately 40% since 1995 and reached a net count of 3.2 billion in such a short span of time. Such increase in data leads to information overload, thus creating a high level of stress and chaos [4]. Thus, in order to save a person from this confusion and make the surfing experience on the Internet better, Recommender Systems (RS) were introduced. Recommendation system is defined as the software technology/tool that makes relevant suggestions to a user. Usually, RS suggests products that a user might find valuable, thus helping both the recipient and the seller. Approximately a decade has passed since the first ever paper on Recommender system but till date there is a void when it comes to a state-of-art survey of Recommender Systems. Hence it provides perfect motivation, to the work to resolve this issue and provides researchers interested in Recommender system with

an all-in-one study focusing on all its types, approaches and challenges. The mapping between different types of Recommender Systems and the challenges have never been covered before, thereby adding more credibility and importance to this work. The idea is to get a clear picture about the limits of each type of Recommender System.

The rest of the paper is organized as follows: the next section expounds the types of Recommender Systems followed by a discussion of the challenges within the domain of RS. Finally a mapping of the open problems in respective recommender system type is uncovered to determine the research gaps in the field of Recommender Systems.

II. TYPES OF RECOMMENDER SYSTEMS

Recommender Systems (RS) are primarily directed towards a class of individuals who lack sufficient Experience/Information or competence, resulting in poor evaluation of high number of alternative items provided by the seller/websites. Literature review suggests that categorization to identify the types of RS can primarily be either on the basis of User's aspect (Personalized & Non-Personalized) or approaches used (Collaborative, Content-based, Demographic, Hybrid). Novel categories, such as Knowledge-based RS & Domain-Specific RS (context/location-based) have also been identified in many relevant studies. The details of these types of RS are discussed in the following sub-sections and are pictorially depicted in fig 1:

A. BASED ON USER'S ASPECT

In this section we will categorize Recommender system based on the user it will be dealt with. If it is made for a particular type of users then it is Personalised RS otherwise it is Non-Personalised RS.

1) PERSONALISED RECOMMENDATIONS

These types of recommendations are given as lists of ranked products. During this task the system tries to recommend/suggest the best matching items/services, depending on recipient's choices [1]. The products can be suggested depending on its visibility & ranking (appearance on the top) of a website, past analysis of user's behavior or demographics of a user as a suggestion for next recommendations for the customer.

2) NON-PERSONALISED RECOMMENDATIONS

These types of recommendations are easier to generate as compared to the personalized recommendations and are

usually used in newspapers and academic journals. The suggestions are independent of the user, therefore everyone tends to get same suggestions. They are automatically generated on the grounds that they require little client effort to create the suggestions and are transient. These proposals are totally independent of the specific client focused by the RS or newspapers/Magazines.

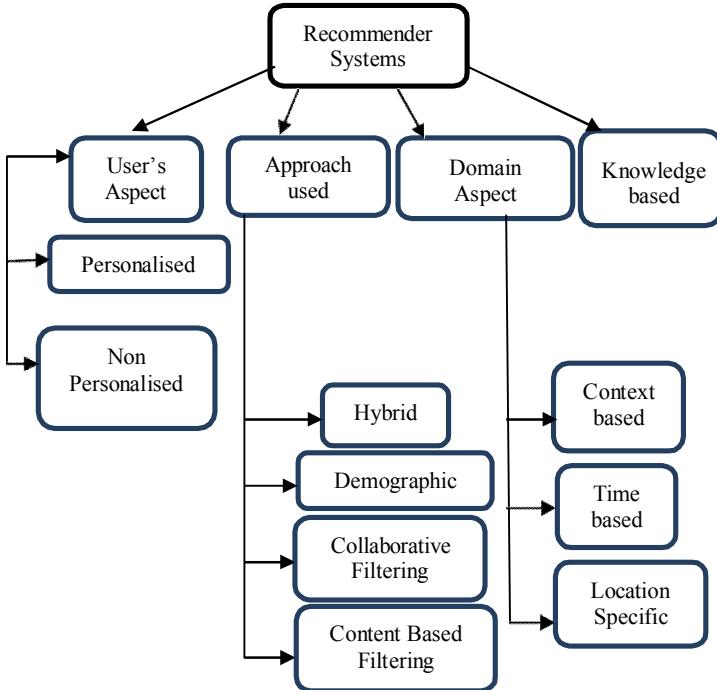


Fig.1. Types of RecommenderSystems

B. BASED ON RECOMMENDATION APPROACHES USED

Recommender systems facilitate users as a tool for finding items of interest. In this section we expound the basic algorithmic approaches used describing the criteria for recommendation. These include collaborative filtering, content-based filtering, demographic filtering, hybrid & knowledge based recommendation approaches which combine basic variants. The following sub-sections discuss the details of these recommendation approaches enlisting their advantages, disadvantages, prominent techniques used and specific application areas.

1) COLLABORATIVE RECOMMENDER SYSTEM

Collaborative filtering (CF) uses the numerical reviews given by the consumers and is based mainly upon the historical data of the user available to the system. It makes suggestions to all dynamic consumers with data about group of consumers and their connection with the item set. Both the consumer profile and the item profile are used to make a recommendation system. It is considered one of the most basic and the easiest method to give suggestions and make predictions regarding a product depending on consumer's previous behavior and the consumer's behavior of other

likeminded consumers. Collaborating Filtering based techniques can further be categorized as follows:

(i) *User-based collaborative Filtering*: Correlation is computed between one user and others user. Also for every data-item we calculate the ratings of the consumers that are heavily related with each consumer [7]. Common problems with these types include data sparsity, bad correlation & ease of getting attacked.

(ii) *Item-based collaborative Filtering*: Correlation is computed between one item and every item set. Most commonly used are the cosine and Pearson correlation similarity approach. Also for every consumer we calculate the consumer's ratings of products that are heavily related with each data-item. Therefore there is less sparsity and at the same time cold start is less influential and so is any type of Attacks [8].

There are three main algorithmic categorization of collaborative filtering:

Memory based: Users and dataset with similar interest are combined

Model based: different techniques involving data mining and machine learning are used to determine complex patterns.

Hybrid CF: Different CF techniques and other RS's techniques are combined

- *Advantages*: These kinds of filtering approaches don't require representation of data in dataset of data-properties but is only based on precision of active consumer's group. Database's scalability is large as it doesn't require manual involvement.
- *Disadvantages*: The products can't be suggested to any consumer until the data/item is either ranked/rated by any another consumer/users or correlated with data-items of same kind from the item set. Usually the persistent consumer's rate very less number of items even tough, there is very large number of products database thus leading to very sparse results. Because of changes in opinions of many of the users finds this approach expensively costly and it also requires a lot of time. One other issue that is predominant with collaborative filtering is sparsity issue and the measures taken to resolve it includes: implicit rating, dimensionality reduction and contentdescription.
- *Techniques*: Unified relevance model, Hybrid CF model, Fuzzy Association Rules and Multilevel Similarity (FARAMS), Flexible mixture model (FMM), Maximum entropyapproach
- *Applications*: Collaborative filtering application is used to recommend befitting information as judged by the community. Collaborative filtering is usually set to work upon very large data sets. It is also used in solving the nearest neighborproblem.

2) CONTENT BASED RECOMMENDER SYSTEM

It focuses on the features of the items. The goal is to create a user profile depending on the previous reviews of the users

and also a profile of the item in accordance with the features it provides and the reviews that has been received for that particular item from the item set [9]. It uses information from the item set and knowledge from the dynamic consumer's .This technique is made from the structural information of properties/content of product/item instead of description of consumer's ratings of the particular dataset. Since it provides suggestions according to user's field of interest and adapts according to user's likes and dislikes, therefore [11], it is also known as adaptive filtering. It compares the content of items of user's interest with the content in the item list. It helps overcome sparsity problem that is faced in collaborative filtering based recommendationsystem.

- **Techniques:** Content-Boosted Collaborative Filtering, FAB Technique, Bayesian hierarchical model (BHM)
- **Advantages:** This approach recommend items from the dataset to the consumer and thereby don't require data of other users and also it don't faces first rater problem i.e., It is can recommend new items/products and rare items for each and every consumer. i.e. helpful in both cold start problem and long tail problem
- **Disadvantages:** In these types of techniques products knowledge is restricted to the initial descriptions/features i.e. explicit specifications of its properties is done[12] i.e. it depends on the information provided explicitly and that too manually.
- **Applications:** Used in situations to deal with cold start problem as it is capable of recommending rare data from the item set. Also, used in confidential places like banking etc.

3) DEMOGRAPHIC FILTERINGSYSTEM

This type of RS uses previous information of demographic knowledge regarding consumers and their views for items that were recommended as a criteria base for suggestions, classifier based on demographic data can be obtained by Machine learning techniques [13]. The display of such info in a consumer's model varies to a large extent.

- **Advantages:** It doesn't require knowledge of ratings given by consumer, which were required by the other main techniques (Content based and collaborative). Demographic approach is fast, simple and straight forward for making depending on fewdataset.
- **Disadvantages:** Compilation of full consumer info is required to get good recommendations which can't be possible [10]. As these types of RS are dependent on consumer's field of interest, it generally results in, recommending the usual data to consumers having same field of demographic interest, thus resulting in too general recommendations. There are security and privacyissues.
- **Applications:** This technique is very well utilized in formulating the recommender system such as trip adviser or a party planner where the demographic information is taken into consideration [14] and so a

new user can also be recommended as it does not requires the user's previous information.

4) HYBRID RECOMMENDERSYSTEM

Hybrid RS is type of RS, efficiently overcomes the limitations of other recommendations approaches. This type of techniques uses the good features of two or more approaches to gain stable and robust system and to have a robust recommender system [15].Collaborative and content-based filtering are the most common hybrid approaches. Mostly, this type of approaches uses both ratings of all users and items as attributes [16]. Usually, such RS adapts Heuristic mixture of collaborative filtering and content based filteringmethods.

- **Techniques:** Weighted, Switching, Mixed, Feature combination, Cascade, Feature augmentation, Meta-level [3]
- **Applications:** As it takes into consideration the best aspect of multiple Recommender system that can practically be used to implement any type of Recommender system eg. Movie data, cab, travel advisor, Website Recommender systemetc.

C. KNOWLEDGE BASED RECOMMENDERSYSTEM:

Knowledge based recommender systems tackle almost all the challenges that were cited in other types. The benefit of such knowledge based recommender systems is that no cold start/ramp up issue persists, as no rating information is required. Recommendations are computed exclusively for every consumer's ratings: either on the basis of explicit recommendation rules or based on the common expects between user needs and product [17]. This type of RS can be categorized in two different categories: constraint based and case-based systems. The way in which they use the knowledge provided is the main difference between the two: case-based recommenders focus on the retrieval of similar items on the basis of different types of similarity measures, whereas constraint-based recommenders rely on an explicitly defined set of recommendation rules [5].

- **Advantages:** One of the biggest benefits of such a Recommender system is that cold-start (ramp-up) problems don't exist in it. The main setback is that, there are potential information extraction bottlenecks, initiated by the necessity of defining information of suggestions in an explicit way [18].Deterministic recommendations can be extracted from knowledge based recommender system as we have assured quality. Also it can resemble salesdialogue
- **Disadvantages:** Cost of knowledge acquisition is very high from domain experts/consumers and from web resources.Knowledge engineering effort to bootstrap is quiet high. This approach is basically static and it does not react to short-term trends.Independence assumption can be challenged as preferences are not always independent from eachother

- *Applications:* This technique can be used to deal with long tail data set such as Recommending exotic villas to users, Poker Recommendationsystem.

D. DOMAIN SPECIFIC CONTEXT-BASED / TIME SPECIFIC/LOCATION BASED RECOMMENDER SYSTEM

Contextual information in a recommender system helps to get a clear view of the situation of any person, place or object which is of relevance to the system for suggestions and anything that can be incorporated. In this kind of Recommender system the contextual knowledge of consumers is also taken into consideration while designing a recommender system [10]. Context refers to the location, time, area and environment of the Consumer which define a user's state. RS requires situational information of the user and context based RS accesses the information directly using various techniques (such as GPS) .The user's location data, social data, current time, weather data are also taken into consideration as the contextual data[19].Contextual factors are of two types: Dynamic and static, depending on whether they change with time or not..

- *Techniques:* Hidden Markov Model, Multidimensional approach, Fuzzy Bayesian Networks, Human memory model, Matrix-factorization Predictive Context Based Model
- *Applications:* Used for recommending the cab or the hotel to the user based on its currentlocation.

III. CHALLENGES IN RECOMMENDER SYSTEMS

Perhaps the biggest issue in having a good RS is that they requires big item set to effectively make suggestions. As a result the companies with a lot of consumer data have excellent and accurate recommendations: Google, Amazon, Netflix, Last.fm [2] .An efficient RS firstly needs item set (from a catalog or by any other way), then it needs to incorporate and analyze consumer dataset (behavioral events), after that the recommender system is implemented on the analyzed dataset. The larger item and user dataset to work with better are the chances of having effective and accurate suggestions/recommendations. The issues in the research domain of RS which have been identified across pertinent literatureare:

- Cold startproblem
- Scalability of theapproach.
- Accuracy of theSuggestions
- Changing dataset
- Impact ofcontext-awareness
- Loss ofneighbourtransitivity
- Sparsity
- Privacyconcerns.
- Recommending the items in the Longtail

Also it may lead to chicken and egg problem i.e. for efficient suggestions, we requires a lot of consumers, so that we get adequate amount of information for the

recommendations there's the requirement of large number of consumers which in turn requires a good and accurate recommender system so as to attract and extract large numbers of users.

1) COLD START PROBLEM

This problem appears at early stages of a recommender system's lifecycle or when a new or rare item/product is added to the dataset. When there is a little knowledge available on a particular item or dataset, ontologies are a proven tool for knowledge extension and extraction [20]. This problem affects every recommender system: the content-based filtering will behave poorly, if there is a little information about the item set. The collaborative filtering also leads to the same result [21]. If the recommender system has no information by using the content-based methods, and there is no user's behavior history in the database/item set, the hybrid approach will produce nearly random recommendations aswell.

B. SCALABILITY AND BIGDATA

This is another important issue in RSs. As ratings database increases, the performance declines exponentially. Systems which can handle large dataset and produce accurate suggestions quickly are required. Trade-off between performance and the prediction accuracy is very common [22]. For example, clustering technique increases performance, but decrease the accuracy. Matrix factorization methods are also not suited for online recommendations with big item sets. This algorithm run on the Netflix Prize competition dataset takes 8 hours to complete the process. Algorithm "Gellyfish", which uses parallelization techniques, reduced computation time of 3 minutes for the Netflix Prize competition dataset. Algorithms' parallelization is a way to solve this problem.

C. ACCURACY OF SUGGESTIONS

Among other details, the user is sensible for false negatives (incorrect recommendations, which the user does not like) which leads to low accuracy in the recommender system. In such cases users lose trust in the RS and stop using it [23]. Therefore, it is important to keep recommendation quality and accuracy at itsbest.

D. CHANGING DATASET

With increase in amount of items and dataset day by day, there is a constant change in the structure of the item set by the constant inclusion of new data in the previous defined item set. Usually an algorithmic approach finds it hard if not impossible to maintain the accuracy with the changing dataset. Most users that are not active face a great issue. They rely on trusted user and groups to recommend and suggest them the new items from the given dataset. This issue can be stated as, biased towards the old and difficult to incorporate new.

E. CHANGING USER PREFERENCE (CONTEXT AWARENESS)

A user being the in taker needs to get details about differenttypes of data from the single contiguous dataset [24]. A classic scenario: sometimes a user will be browsing flipkart

for gadgets, but next moment the same user will be on Amazon searching for a gym kit[25].

F. LOSS OF NEIGHBOR TRANSITIVITY

Situations with the Transitive nature are usually not taken into consideration in the Recommender system. Assume that user 1 is highly correlated with user 2, which in turn is highly correlated with user 3. Also user 3 can in turn be highly correlated with user 1. Such relationships are not captured by recommender systems, but can be done with knowledge of users from, for instance, ontology [26]. For example, user aggregating 75-100 are correlated as intelligent ones, whereas users aggregating 35-50 as average one.

G. SPARSITY

It's very usual that user usually purchase or rate relatively few items compared with the total item set which in turns leads to a sparse users-items represented with matrix and, thereby making it difficult to locate neighbors or derive common behavior patterns resulting in low accuracy system[27]. Latent factor models algorithms can be used to address this issue, which utilizes dimensionality reduction of various users and items resulting in finding patterns in reduced dimensional space, which in turn is not sparse. Matrix factorization methods were good during the Netflix Prize competition they were applied to a 99% sparse matrix with 8.4 billion values missing in the competitions[28].

H. PRIVACY

Personal data collected by RS should be kept safe and piracy must be neglected and should be uninfluenced and unmodified. There are three aspects to be taken care of:-

- Value and risk of personal information
- Shilling
- Distributed Recommender System

In value and risk of personal information we need to determine when to stop collecting the info to balance the privacy and to intelligently choose which info is to be discarded and which to keep. Techniques such as Cryptosystem and zero knowledge are to be used to counter different security and privacy attacks[29].

I. LONGTAIL

About the \$1 Million prize offered by Netflix for a third party to deliver a collaborative filtering algorithm that will improve Netflix's own recommendations algorithm by 10%, we noted that there was an issue with eccentric movies[6]. Long-tail phenomena are ubiquitous in real world applications, challenging the task of information trustworthiness estimation. Sources with very few suggestions and items in the dataset are common in applications [30]. Such low number of items (rare items) and suggestions exhibited by user typically exhibits long-tail phenomenon, i.e., most of the users only provide data about one or two items, and there are only a few users that make lots of suggestions [31]. For example, There are numerous sites containing info/knowledge about one or many celebrities, there are few sites which, like Amazon, Wikipedia, provide extensive coverage for thousands

of celebrities. Also low number of user participation in survey, review or other activities. On average, participants shows suggestions to few items whereas very few users cover most of the items. ZiedZaier et al. introduced long tail issue and its effects on RS. That provides a review of the different item sets which were used to examine and check collaborative filtering RS algorithms and techniques. Also the effects of various RS techniques depending on different item set were also compared. The study details and covers a single-criterion item set's rating similar to almost all of current collaborative filtering RS. The Table 1 depicts the mapping between different types of Recommender systems and the challenges thus providing an insight to the open problems within the recommender system diversity.

TABLE I. MAPPING RS TYPES TO ISSUES

Challenges	Types of Recommender Systems					
	Collaborative RS	Content based RS	Demographic RS	Hybrid RS	Domain Based	Knowledge based
• Cold start problem	?	✓	✓	✓	?	✓
• Scalability of the approach.	✓	✓	✓	?	X	X
• Big-data	✓	✓	✓	?	X	X
• Privacy concerns.	✓	X	✓	✓	✓	✓
• Sparsity	X	✓	X	✓	?	?
• Recommending the items in the Long tail	?	✓	✓	✓	?	✓
• Accuracy of the Suggestions	?	✓	X	?	X	X
• Changing data set	✓	✓	X	✓	✓	?
• Impact of context-awareness	?	✓	?	✓	✓	?

IV. CONCLUSION

This study investigated the diversity in Recommender Systems discussing the scope and practical use of each. The existent challenges within the research domain of recommender system are ascertained from pertinent literature and finally a mapping of the open problems to the type of recommendation system is given. The idea was to probe issues that were valid for specific type of RS and which spanned across types. The findings clearly suggest the challenges as opportunities within the research area.

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Teaching and Learning Cultural Metacognition in Marketing and Sales Education

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ABSTRACT

Thinking about cultural assumptions, referred to as cultural metacognition, can help increase awareness, build trust, and create successful marketing and sales outcomes. The role of cultural metacognition in marketing and sales education helps students build a cultural metacognition knowledge base and promotes appreciation of its importance and effect on business enhancement. The context of this article will help amplify knowledge, ideas, and skills necessary to connect various issues of teaching and learning cultural metacognition. This article will facilitate business educators' teaching practices that foster learning cultural metacognition and its effects on marketing and sales. The ultimate goal is to help elevate teaching, learning, and assessment practices related to the topic of cultural metacognition in marketing and sales education.

KEYWORDS

Classroom Assessment Tools, Cultural Intelligence (CQ), Cultural Knowledge, International Business

INTRODUCTION

Metacognition is the knowledge about and regulation of cognition, comprising the processes of monitoring and adjusting thoughts and strategies as one learns new skills (Flavell, 1979; Triandis, 1995). Metacognition is a vital part of the four components that make up Cultural Intelligence (CQ) (*motivational, cognitive, metacognitive, and behavioral CQ*) which is based upon Sternberg's multiple loci of intelligences (Ang, Van Dyne, & Tan, 2011) and can be referred to as *cultural metacognition*. Specifically, cultural metacognition is thinking about cultural assumptions, and helps increase awareness and build trust in cross-cultural relationships. It is an affective skill in reflecting on cultural assumptions, in preparation for, adaptation to, and learning from intercultural interactions (Earley & Ang, 2003; Earley, Ang, & Tan, 2006; Klafchek, Banerjee, & Chiu, 2008; Thomas, 2006).

Cultural metacognition is important because people come from many different backgrounds and societal groups, with fundamental differences in worldviews, ethical standards, and social structure. Employees and stakeholders are completely international, and business decision-making becomes more complex as it applies to employees and stakeholders of different cultures. A complete knowledge base of cultural metacognition is essential for business managers to appreciate the importance of different cultures, and to recognize their own cultural uniqueness and the affect it has on business enhancement (Morris, 2012).

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According to Morris (2012), gaining awareness of personal assumptions can build trust and take a team beyond cooperating on a task, to true creative collaboration. Cultural metacognition in marketing and sales is a vital element in the 21st century. In terms of educational and practical implications, future business success requires training and harnessing metacognitive habits among students and managers (Mor, Morris & Joh, 2013).

BACKGROUND

In his seminal work, Hart (1965) talked about the “feeling-of-knowing” experience linked to long-term memory, which forged the way for further studies focused on metacognition. Flavell (1976, 1979, 1987) used the term metacognition to present a conceptual model of cognitive monitoring. This encouraged educational researchers to develop interventions that would increase cognitive monitoring, on the premise that cognitive monitoring would lead to better learning. Flavell’s model identified metacognition as one’s self-knowledge about cognition (metacognitive knowledge) and regulation of cognition (metacognitive regulation), or strategies for doing so. Flavell felt that everyone has the ability to monitor, track, evaluate, and change their thinking and learning processes.

Chua, Morris, and Mor (2012) gathered from research that cultural metacognition is a skill that enables individuals to reflect on “cultural assumptions in order to prepare for, adapt to, and learn from intercultural interactions” (p. 116). More than just simply knowing about culture, it includes the skill of understanding and collaborating knowledge. It involves the skills of monitoring, evaluating, and coordinating cognitive processes that help advance business practices.

Intercultural effectiveness requires forging close working relationships with people from various cultural backgrounds (Black, Mendenhall, & Oddou, 1991). Interactions with people from various cultures expose students and colleagues to ideas and angles that add new insights and diversity (Chua, Morris, & Mor, 2012). “The habit and skill of thinking about one’s own and other’s culturally based assumptions presumably enables individuals to communicate better, to put people at ease, and to avoid misunderstandings and tensions” (Chua, Morris, & Mor, 2102, p. 117). Conversely, the failure of managers from various cultures and countries to work effectively with one another can lead to business-structure demise (Hagel & Brown, 2005).

MAIN FOCUS OF THE ARTICLE

The context of this article will help to amplify ideas necessary to connect issues of teaching, learning and assessing students’ cultural metacognition for cross-cultural environments. The ultimate goal for educators is to enable students to move their cognitive knowledge to a higher level of metacognition, where they are active, self-monitoring, and goal-directed, and embrace an internal locus of control over their own learning.

The three basic framework strategies for fostering metacognition are: connecting new information to former and current knowledge; selecting deliberate thinking strategies; and planning, monitoring, and evaluating the process (Dirkes, 1985).

One way to assess students’ understanding of cultural metacognition is by using Classroom Assessment Tools (CATs). CATs are ungraded activities that help educators assess what was taught. CATs help students by increasing their ability to think critically about what was being taught. CATs help educators “...obtain useful feedback on what, how much, and how well their students are learning” (Angelo & Cross, 1993, p. 3).

Following are some practical tools/strategies that can inform cultural metacognition.

Web-Based Platforms

Web-based platform tools are available in the marketplace which can assist users with how to test their assumptions about a culture in which they may not be competent. These platforms help users analyze cultural preferences to improve cross-cultural collaboration. One example is the Cultural Navigator (see www.culturalnavigator.com).

Mentoring

Mor, Morris, and Joh (2013) suggest that teachers consider assigning students who score higher on cultural metacognition negotiate or work on class assignments with students who score low on cultural metacognition competencies. This method is applicable in the field as well where managers well embedded in metacognitive habits could assist those with less metacognition competencies.

Modeling

Modeling is an effective way to learn. Teachers and business leaders play vital roles with both the learner and the learning environment. The classroom and the field afford the opportunity for educators and leaders to model cultural metacognition skills, which can have a significant impact on those being taught.

Feedback

Mor, Morris, and Joh (2013) recommend the use of performance feedback as a way to develop awareness and planning habits. This could help show students where their metacognitive strategies might benefit from more training or harnessing. Lane (2007) teaches techniques for adapting the behaviors of virtual humans to promote cultural learning, as well as explicit approaches to feedback. These techniques help the learner recognize cultural difference and improve their ability to self-assess in an interpersonal context. High-fidelity simulations create realistic portrayals of different cultures in terms of architecture, dress, sounds, art, and even smells. According to Lane (2007), this can promote a learner's sense of immersion, and provide a foundation for identifying *objective* cultural differences.

Further, Lane details the use of *experience manipulation*, a technique that simulates an event or situation that promotes learning. This occurs through computer technologies that simulate real-world phenomena. Implicit feedback about oral and gestural reactions of virtual humans is solicited, so that participants can recognize any cultural errors, and experience accentuating positive and laudatory responses to correct user actions. Explicit feedback can also be helpful, where a pedagogical agent explains the cultural differences in play during specific interactions or warns against risks. Further details about experience manipulation can also be found in Lane and Johnson (2008), and Wray, Lane, Stensrud, Core, Hamel, and Forbell (2009).

Schemas

Schemas (knowledge structures) are sets of propositions or mental constructs that create generalizations and expectations about categories of objects, places, events, activities, and people. According to Earley and Peterson (2004), metacognition is critical for developing shared schemas. Research has shown that when certain schemas are applied in an intercultural-communication context, it could cause misunderstandings in the process. From implicit schema, explanations are derived for contradictory behavior to go with our schemas (e.g., if a professor is late, students might think some emergency arose; but, if the professor is consistently late, then students may decide he is an inadequate professor). One way of thinking about schemas is by working in intercultural teams where participants can learn, assess, and strategize.

Field-Based Learning

Another practical strategy to learn and practice cultural metacognition is through field training. Field training helps promote lived experiences that not only foster opportunities for higher levels of competencies, but also opportunities to foster higher order thinking.

Formative Assessments

Research has shown that formative assessment helps improve student metacognition and reflection (Black & Wiliam, 1998; Cizek, 2010). The National Council of Teachers of English (NCTE) groups formative assessments into four types: observations, conversations, student self-evaluations, and artifacts of learning (NCTE, 2013). Specific tools and strategies of formative assessments include surveys, interviews, and conferences, as well as field notes in which teachers record descriptions of students' classroom interactions. Student self-evaluations are important components of formative assessment and metacognition, as they provide opportunities to reflect on goal progress. Artifacts of formative assessment are helpful for teachers, because they create opportunities to review data about individual students or groups of students, to support planning future learning experiences. For example, teachers may collect a variety of sources of information on a single learner (e.g. case study), in order to identify patterns of understanding for further analysis and learning (Pinchok & Brandt, 2009).

Building Respect

Being perceived as uncaring, whether overtly or indirectly through tone of voice or body language, can cost respect. In a qualitative study with youth, Price-Mitchell (2010) found that real-world service interactions with people who are suffering led to overcoming interpersonal challenges and transformational development of initiative, purpose, and civic identity. Meditation also increases compassionate response to others who are suffering (Condon, Desbordes, Miller, & DeSteno, 2013).

To fill the gap between theoretical and practical implications, educators can help their students understand more about respect for others by assigning them projects that integrate tasks that involve helping others in need, through charitable contribution or research. In fulfilling this task, students write about and discuss cultural awareness and the biases these experiences may have revealed.

Building on the notion that having conversations with strangers can promote rapport (Drolet & Morris, 2000), educators can ask students to have a personal conversation about the feelings they have in common with others they do not know.

Building Trustworthiness

The creative potential of cross-cultural interaction flows through trust (Chua, Morris, & Mor, 2012). The sharing of new ideas requires trust and the confidence to rely on others (McAllister, 1995). Those with higher levels of cultural metacognition are more likely to develop trust in their intercultural interactions and relationships (Chua, Morris, & Mor, 2012). Trust is a crucial factor for team performance. Without trust, team members are unlikely to voice their opinions, ask questions, or present ideas. In addition, without trust, team members are less likely to display their feelings or help others (Erdem, Ozen, & Atsan, 2003). All these aspects are crucial in co-creation of business networks and the building of high-performing teams (Hakanen & Soudunsaari, 2012). Chua, Morris, and Mor's (2012) research suggests that the sharing of new ideas depends greatly on true feelings and concern for one another (affect-based trust), not merely cognitive-based trust.

In terms of practice, Price-Mitchell (2010) suggests integrating five values (responsibility, respect, fairness, trustworthiness, and honesty) into the curriculum, and helping students use the vocabulary to discuss a variety of historical topics and current events. As a tool for teaching, since dishonesty and disrespect flourish in civil society, educators could ask students to find examples of how individuals stood up for their beliefs and values in ways that made a difference for themselves, or for the world.

This could help students think about others' experiences as well as their own assumptions, and to share with each other and learn from one another in the process.

Hakanen and Soudunsaari (2012) say:

Business partners do not commit fully to business network development without trust, both at the personal and business-concept levels. Enhancing trust needs a community of enrichment and regular interaction between all partners. Also, value creation and shared learning could be increased if high-trust relations are built. One of the key ingredients for better communication is genuine listening and respect for other team members' ideas. This study has also shown that fact-based communication alone does not build personal relations. Trust takes time to develop, but without conscious actions like one-on-one meetings with different partners and team-building exercises, the probability for success decreases. (p. 40)

Integrative models suggest that coaching designed to cultivate affectual and personal connections can be valuable early in a team's work together (Hackman & Wageman, 2005). Team-building training helps instill those affective bonds that are necessary to help build unpretentious relationships (Moreland & Myaskovsky, 2000).

Building Responsibility

Organizational ethics are not primarily driven by policies and procedures, but by the actions of leaders (Porter, 2014). Building social responsibility can help foster cultural metacognition. For example, teaching tasks that enable responsibility and propriety can foster meaningful relationships. This falls under the learning principle that one's actions affect others. Teaching students how to monitor or think about their actions can help foster metacognition in a positive direction. For instance, educators can provide students with various scenarios that can help them see how actions affect others.

Scenario example: Several multicultural participants hold a business meeting in which all favor setting a mutual agenda. Due to language and cultural barriers, one participant in particular is struggling to keep up and continually asks for clarification. One annoyed colleague begins to complain about repeated interruptions. The colleague's tone is rash and unfriendly.

Questions to consider:

1. How do you think this makes the person who is struggling and needful of clarifications feel?
2. What effect might the response of this colleague produce on the other participants?
3. How could this affect the outcomes of the business agenda?
4. What other options could be considered in dealing with this scenario?
5. What would be the responsible way to handle this situation?

Building Fairness

The Foundation Institute for Visual History and Education (2006) has developed an exercise that educators can use, titled "Creating Character: Visual History Lessons on Character Education." The project is designed to help students develop an understanding of the concepts of justice and fairness, working from visual-history testimonies. Students are asked to explore their own viewpoints regarding justice, and to identify steps they can take to promote justice and fairness. This educational task helps to promote higher levels of metacognition skills. Students are asked to complete the following tasks and corresponding questions:

1. Choose six student volunteers to participate in an experiential activity. Explain to the rest of the class that during this activity, they will be observing and recording the reactions of the volunteering participants;

2. Seat the six volunteers at the front of the room, facing the class. Explain to the volunteers that they are participating in a quiz show and that students who answer questions correctly will be rewarded;
3. Prior to beginning the questioning, secretly identify one or two participants against whom you will actively discriminate during the activity. This discrimination may be based on either a real difference (eye color, hair color, left-handedness, etc.) or it may be a random choice;
4. Begin asking the six volunteers relatively easy questions. These questions can be based on other lessons in this resource, on material that the class has previously covered, on current events, or on easy topics of student interest. Reward students who correctly answer the questions with something tangible, such as candy, stickers, stars, pens, or extra credit points. Do not acknowledge the responses from the student(s) who you have decided to actively discriminate against;
5. Continue the questioning process for approximately three to five minutes;
6. Once the activity has concluded, instruct all students, participants, and observers alike to silently reflect upon and write about this experience. Make sure students address the following: What exactly happened during this activity? What do you think was actually happening? What were the reactions of the participants during the activity? At what point did it become evident that certain participants were being treated unfairly? What were their general feelings about the activity? (p. 1)

Building Honesty

There tends to be a lack of realism and truth telling in interactions at work. Often people are forced to say what they think others want to hear, rather than what they believe to be true. As a result, workers don't become real in their expectations, thinking, and interactions. After a while, no one asks for opinions and thoughts because they know they aren't getting the truth. They basically give up.

When this happens within an organization, attempts at achieving "engagement" ends up being nothing more than a charade. In particular, if people don't think their leaders are being honest, they are not going to trust them, and if they don't trust them, decision making, communications, relationships, and results are affected. And the same happens on the flipside, if leaders just think their people are telling them what they want to hear, then they'll stop asking; clearly not a great scenario (Root White Paper, 2017).

One pedagogy that can be used to teach honesty is to illustrate a work culture that can actually point out what is not honest.

Questions for students consider:

1. Why do you believe there is a lack of realism and truth telling in interactions at work?
2. How can building honesty improve cross-cultural relationship building?
3. How can leaders model honesty?
4. What are the benefits of transparency?
5. What are the risks of transparency?
6. What are some ways to break through the barriers that block honesty?

Monitoring

Teaching students to monitor their cognitive processes is an important step toward building cultural metacognition practice. There are several ways to enhance students' monitoring techniques.

Monitoring involves continually checking for understanding. In terms of practice, educators can teach students to self-monitor their cultural understanding by reflection that includes looking at biases, awareness, sensitivities, inclusiveness, and relationship to business outcomes.

Educators should start by introducing self-awareness and self-monitoring skills. Students and educators should discuss key strategies for learning how to self-monitor. These sessions can include group activities designed to help students think about these new skills and apply them in practical ways.

For example, after initial sessions designed to teach self-monitoring skills, students could participate in staged groups that incorporate various cultural scenarios. One student could be staged as someone from a majority culture, and then interact with others who portray persons from a minority culture. After a few rounds of interactions, the students can report back their experiences and how the use of self-monitoring was applicable in the scenarios.

Another skill is monitoring one's own macroaggressions and microaffirmations. Microaggressions are small events or subtle acts of disrespect, which are often hard to prove, sometimes covert, and often unintentional, but which may lead to the perception of discrimination or harassment (Sue, Capodilupo, Torino, Bucceri, Holder, Nadal, & Esquilin, 2007). Microaffirmations are micromessages that convey inclusion, respect, trust, and genuine willingness to see others succeed (Rowe, 2008). Microaffirmations may lead to a more productive and efficient work environment, where all members feel valued and enjoy work. Research also shows that these "small" messages have power for insiders and outsiders (Wong, Derthick, David, Saw, & Okazaki, 2014). For example, when a person with higher status acknowledges someone at a meeting, that acknowledgement influences others to also think more highly of that acknowledged person.

Evaluating

It is important that students evaluate the cultural or personal differences that may be enhancing or limiting their potential to interact in a multicultural world. Getting an accurate picture requires gauging cognitive, relational, and behavioral differences, along various dimensions where cultural gaps are most common, and to assess in those areas. The 20-item, four factor *Cultural Intelligence Scale (CQS)* was developed to test and validate Earley and Ang's (2003) conceptualization of CQ. The CQS measures the four primary factors which represent CQ capabilities (Drive, Knowledge, Strategy, and Action CQ) (Van Dyne, Ang, & Koh, 2008). The CQS possesses good metric properties that has both applied and empirical potential (Van Dyne, Ang, & Koh, 2008).

There are several cultural awareness self-assessment forms available that educators could introduce to their students. These assessments can help provide a starting point for students to build a more comprehensive evaluation of themselves, as it relates to how they think about cross-cultural situations. *The Cultural Awareness Self-Assessment Form 3* is free for public access and is a good tool to help broaden awareness.

The *Cultural Competence Checklist: Personal Reflection* is a tool developed by the American Speech-Language-Hearing Association to heighten awareness of how professionals view clients/patients from culturally and linguistically diverse (CLD) populations (American Speech-Language-Hearing Association, 2010).

Another way to evaluate awareness is by using the *Implicit Association Tests (IAT)* (see <https://implicit.harvard.edu/implicit/takeatest.html>). Implicit biases are those we carry without awareness or conscious direction. These tests have documented existence of bias on a range of dimensions of diversity (e.g., gender, race, ethnicity, age, skin tone, sexual orientation) and in a range of cultures/contexts. These tests measure and compare response times to identify unstated biases, a great way to increase awareness. The underlying theory is that we will respond more accurately and quickly to associations that fit with our own implicit social cognitions—that is, those acquired associations that are largely involuntary (Greenwald, McGhee, & Schwartz, 1998; Banaji & Greenwald, 2013). A comprehensive toolkit developed by the American Bar Association, to teach practical ways of dealing with implicit bias, could be an excellent tool for educators to adapt (see Marmer, Ridgeway, Sherman, Bass, & Epps, n.d.).

FUTURE RESEARCH DIRECTIONS

Future research could focus on the human ability to monitor, track, evaluate, and change one's thinking and learning processes, as it relates to cross-cultural relationships. Both qualitative and quantitative research will help advance our knowledge of cultural metacognition.

As discussed, research on metacognition in general is fairly rich; however, specific research dedicated to cultural metacognition is evolving. Findings from research in educational and cognitive psychology show that metacognition exerts substantial influence on individual performance. The majority of this research examines metacognitive skill as it applies to academic settings; however, studies of other contexts, such as cross-cultural settings, are needed. Vich (2015) recommends that researchers extend their examination of individual effects to the effects in working-group relationships.

Given earlier findings, Mor, Morris, and Joh (2013) hypothesize that cultural perspective taking (i.e., considering how another's cultural background shapes behavior in a given context) facilitates intercultural coordination and cooperation. Manipulation that boosts cultural perspective taking would especially benefit individuals who score low in dispositional cultural metacognition. Future research along these lines could examine the cultural-metacognition effects of assigning students scoring higher on cultural metacognition to negotiate or work on class assignments with students scoring low on cultural metacognition. Better understanding of cultural perspective taking calls for additional research, exploring the ability to accurately detect culture-specific congruent or incongruent norms, which may require the development of metacognitive habits in tandem with foreign cultural knowledge (cognitive CQ).

More research is needed to expand on the theory that links cultural diversity with creativity, as findings suggest that conditions that allow collaboration of different cultures help increase creativity (Chua, Morris, & Mor, 2012). Finding out what dynamics in teamwork suggest effective intercultural creative collaboration requires more research with multicultural teams. Expanding organizational research with diverse social and communicative networks, and considering what innovations are needed to advance business, are recommended.

Narrative research can be effective in determining communication expectations. Research built on narrative works by Gertsen and Söderberg (2011) could enable further study of how to adjust and learn during communication across cultures, to build mutual understanding, respect, and trust that could advance business practice.

Research on the role of affect is also needed, as this is the high-order taxonomy most closely related to metacognition. Cultural metacognition is associated with affective closeness and creative collaboration in intercultural relationships. However, we must learn more about those with low cultural metacognition who often rely on pejorative stereotypes about cultural out-groups, and do research on what interventions would be best—in other words, how to build on the work of Chua, Morris, and Mor (2012), who found that individuals' perceptions of colleagues' reliability and competence probably do not hinge as much on the quality of their interactions, as they do on their affective feelings toward their colleagues. Finally, intervention research is needed to find out how to build affect among those involved in cross-cultural business.

CONCLUSION

Cultural metacognition in cross-cultural business education is a vital element in the 21st century. A complete knowledge base of cultural metacognition is essential for students and business managers to appreciate the importance of different cultures, and to be aware of their own cultural uniqueness and the affect it has on business enhancement. Cultural metacognition involves monitoring, evaluating, and coordinating cognitive processes that help advance cross-cultural business practices. For managers, intercultural effectiveness requires forging close working relationships with people from different cultural backgrounds.

This article is unique in providing the reader with a new pedagogy to help facilitate business teaching practices, through practical strategies and educational tasks that will foster learning cultural metacognition and how it affects cross-cultural business practice. Bridging the gap between theory and practice, it elevates readers' teaching, learning practices, and research related to the topic of cultural metacognition in cross-cultural marketing and sales education.

Cultural metacognition builds on the fundamental values of higher-order academic integrity (e.g., responsibility, respect, fairness, trustworthiness, and honesty). Learning these values in practical ways fosters cultural metacognition knowledge base development and implementation. Finally, educational and practical implications, of training and harnessing cultural metacognitive habits among students are vital for success.

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