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Detecting latent topics and trends in educational technologies over four decades using structural topic modeling: A retrospective of all volumes of *Computers & Education*

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ABSTRACT

Computers & Education has been leading the field of computers in education for over 40 years, during which time it has developed into a well-known journal with significant influences on the educational technology research community. Questions such as "in what research topics were the academic community of *Computers & Education* interested?" "how did such research topics evolve over time?" and "what were the main research concerns of its major contributors?" are important to both the editorial board and readership of *Computers & Education*. To address these issues, this paper conducted a structural topic modeling analysis of 3963 articles published in *Computers & Education* between 1976 and 2018 bibliometrically. A structural topic model was used to profile the research hotspots. By further exploring annual topic proportion trends and topic correlations, potential future research directions and inter-topic research areas were identified. The major research concerns of the publications in *Computers & Education* by prolific countries/regions were shown and compared. Thus, this work provided useful insights and implications, and it could be used as a guide for contributors to *Computers & Education*.

1. Introduction

Technologies have a significant impact on humans and society. They have changed our ways of thinking, feeling, and acting, as well as how we communicate and obtain knowledge (Kenski, 2008, p. 21). The ways we learn and teach have been dramatically influenced by technological advancements (Martin et al., 2011), and technology used for educational purposes has been progressively growing (Berrett, Murphy, & Sullivan, 2012; Inan; Lowther, 2010).

Many universities and academics incorporate innovative technology-based educational methods both inside and outside the classroom to suit different learners' needs and to stay competitive within the worldwide educational markets (Stacey & Gerbic, 2008; Garrison & Kanuka, 2004). There has been increasing interest in the uses of technology among teachers and educators since the early 2000s (Bonk & Graham, 2005) through face-to-face and online instructions for course teaching (Margulieux, McCracken, &

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Catrambone, 2016).

In academia, instructional and educational technology-related scholarly journals began to appear in the 1970s (Zawacki-Richter & Latchem, 2018). Since then, research into technologies use for educational purposes has become an increasingly active area, with continuously growing interest (Martin et al., 2011). There have been several up-to-date reviews on the use of technology for educational purposes, which have depicted the current status of the field and its development (e.g., Wang, Hou, & Tsai, 2019; Chou, Wu, & Tsai, 2019; Lin, Tang, Lin, Liang, & Tsai, 2019). For instance, Chang, Lai, and Hwang (2018) reviewed studies published in academic journals during the period 1971–2016. Nagendrababu et al. (2019) reviewed studies in relation to technology-based learning for endodontics courses. Crompton and Burke (2018), as well as Pedro, de Oliveira Barbosa, and das Neves Santos (2018), conducted reviews concerning mobile learning. River, Currie, Crawford, Betihavas, and Randall (2016) examined the effectiveness of blending technology with team-based learning. Tondeur, Van Braak, Ertmer, and Ottenbreit-Leftwich (2017) conducted systematic reviews to investigate how the pedagogical beliefs of instructors related to their technology use for teaching. A literature review by Kirkwood and Price (2014) discussed the technologies adopted to enhance teaching and learning in higher education institutions. Inglis and Foster (2018) conducted an analysis of all the publications in *Educational Studies in Mathematics* and *Journal for Research in Mathematics Education* to explore how mathematics education has developed over the last five decades. A summary of some of the recent review studies on technology use in education as well as relevant topics published in *Computers & Education* is provided in Table 1. The aforementioned reviews either focused on a particular field of education (e.g., nursing or mathematical education) or a specific technology (e.g., mobile technology), or were conducted based upon meta-analyses rather than using quantitative methodologies. Furthermore, there are two limitations of these review studies. First, as most studies used meta-analysis and manual coding methods, the numbers of articles that were reviewed in these studies were relatively limited (i.e., from 22 to 139). Second, manual coding, which was the predominant approach adopted in these studies, might be inaccurate, as it involved a tedious and laborious coding process. Therefore, it is necessary to employ a computational method suitable for sizeable bibliometric datasets obtained from a representative journal in order to address the above limitations of the existing review studies and to provide an overview of the trends and directions within the educational technology field.

Bibliometric analysis is increasingly accredited as an invaluable and effective technique for evaluation of academic outputs within a specific research field (Moed, De Bruin, & Van Leeuwen, 1995); in particular, it can be employed to obtain a better understanding of what has been investigated in the past and further make predictions about what will happen in the future (Morris, DeYong, Wu, Salman, & Yemenu, 2002). It has been widely applied in scientific research trend analysis, as well as identification of emerging topics within a particular research area (Chen et al., 2018a, 2018b, 2019a, 2019b, 2020; Hao, Chen, Li, & Yan, 2018; Song, Chen, Hao, Liu, & Lan, 2019). Notably, bibliometric analysis is a popular choice for evaluating the academic outputs of a specific publication source. For instance, Cobo, Martínez, Gutiérrez-Salcedo, Fujita, and Herrera-Viedma (2015) conducted a quantitative review of the academic literature published in *Knowledge-Based Systems* during the period 1991–2014, and Zawacki-Richter and Naidu (2016) illustrated the development trends of *Distance Education* by reviewing 515 publications during the period 1980–2014.

This study focused on the publications of *Computers & Education* for the following reasons. Firstly, according to Journal Citation Reports,[1] *Computers & Education* is the third most influential journal in the Education & Educational research category, immediately after the *Review of Educational Research* (a review-focused journal) and *Educational Psychologist* (an educational psychology-focused journal). Of the top three, *Computers & Education* is the only journal specialized in technology use in education. Secondly, *Computers & Education* publishes considerable ranges of articles concerning digital technology use for educational purposes. Thus it has a wide range of research foci and has attracted great interest from the broader educational community. In addition, *Computers & Education* is not only a well-known journal with well-recognized academic influences on computer-based education (Zawacki-Richter & Latchem, 2018), but also has witnessed the shift from discussing the potential of adopting technologies for educational purposes to exploring how to adopt such technologies for educational purposes. With the basis of the aforementioned reasons, we concluded that studying the perspectives and interpretations of theories, the research findings, and the application practices of *Computers & Education* can help identify the frequently investigated research issues, researcher-developed tools, and commonly accepted theories (Zawacki-Richter & Latchem, 2018; West, 2011).

(Echeverria, Nussbaum, Albers, Heller, Tsai, & van Braak (2019)) explored whether a set of metrics, for example, how many times a publication has been downloaded online, or how many times a publication has been shared on social media platforms, were able to provide implications for the social influences of the *Computers & Education* publications. In addition, based on 3963 *Computers & Education* articles published during the period 1978–2018, Chen, Yu, Cheng, and Hao (2019c) identified several prolific and influential authors and depicted their scientific research collaboration relations. They also identified frequently used keywords and influential countries/regions and institutions based on the H-index. Although their study used the same dataset as us, this study differ from their work in the following aspects. First, the present study had more analyses from the perspective of countries/regions and institutions , attempting to identify the most productive ones. From the perspective of research topics , this study adopted a markedly different method (i.e., topic modeling), using as its basis not only author-defined keywords but also keywords extracted from titles and abstracts. Additionally, a review work by Zawacki-Richter and Latchem (2018) mapped the research topics covered in *Computers & Education* between the years of 1976 and 2016, with the help of a Leximancer tool based mainly on co-word and clustering theories. They pointed out that *Computers & Education* articles predominantly covered four research areas over that period. To be specific, during the period 1976–1986, the community concerned more about the development and growth of computer-assisted teaching. During the period

[1] https://jcr.clarivate.com/.

Table 1
Summary of the recent review studies on technology use in education, as well as relevant topics published in *Computers & Education*.

Study	Topic	Number of reviewed articles	Methods	Research issues
Xie, Chu, Hwang, and Wang (2019)	Technology-enhanced adaptive/personalized learning	70	Manual literature coding according to a scheme based on the constructivism theory framework	Distributions of learners, learning outcomes, system/hardware, learning outcomes, and parameters of adaptive/personalized learning.
Rodrigues, Almeida, Figueiredo, and Lopes (2019)	Electronic learning	99	Manual literature coding	What e-learning referred to in various academic fields, the usability in the e-learning context, and learners' attitudes towards e-learning.
Chung, Hwang, and Lai (2019)	Experimental mobile learning	63	Manual literature coding according to a scheme based on the activity theory framework	Six dimensions, including subjects, objectives, contexts, tools, control, and communication.
Burden, Kearney, Schuck, and Hall (2019)	Innovative mobile pedagogies for school-aged students	57	Manual literature coding	Different types of advanced and disruptive mobile instructions for learners, and to what degree advanced mobile instructions interrupted teaching and learning.
Xia and Zhong (2018)	Teaching and learning robotics content knowledge in K-12	22	Manual literature coding	Nine main issues for each study, including sample groups, robotics content knowledge, measurement instruments, research findings, and instructional suggestions.
Akçayır and Akçayır (2018)	Flipped classroom	71	Manual literature coding	General features of the studies, for example, annual trends and learner types, as well as advantages, challenges, and activities of the flipped classroom.
Fu and Hwang (2018)	Mobile-enhanced collaborative learning	112	Manual literature coding according to a scheme based on the constructivism theory framework	Issues such as statistical distributions, participants, research methods, application subjects, learning devices and contexts, research issues, learning strategies, and relationships between learning strategies and measurement issues.
Chang et al. (2018)	Mobile learning studies in nursing education	97	Manual literature coding according to a scheme based on the constructivism theory framework	Issues such as subjects, application domains, research issues, learning strategies, as well as important findings.
Bray and Tangney (2017)	Technology usage in mathematics education	139	Manual literature coding	Pedagogical foundations, digital tools, goals of the activities, as well as the levels of the integration of technology.
Money and Dean (2019)	Learning online in higher education	36	Manual literature coding	Main types of antecedents and processes, and factors that affect learning outcomes.

1987–1996, the community focused mainly on stand-alone multimedia learning. In the period 1997–2006, issues relevant to networked computer use for enhancing collaborative learning showed precedence. Online learning attracted more attention during the period 2007–2016. Yet, for topic detection and tracking, topic modeling is considered more flexible and effective than alternative approaches such as document clustering (Kuhn, 2018). Topic modeling serves as a natural language processing method to uncover topics hidden within large quantities of textual data (Nielsen & Börjeson, 2019). It has been proven to be a valuable and suitable tool to uncover meaningful topics from substantial quantities of text data (Jiang, Qiang, & Lin, 2016; McFarland et al., 2013; Nichols, 2014). Wide ranges of recent studies have been conducted to apply topic modeling to research areas concerning social sciences (e.g., Vilares & He, 2017; Hannigan et al., 2019; Park, Chung, & Park, 2019; Franz, Nook, Mair, & Nock, 2019; Ye, Zhao, Shang, & Zhang, 2019; Houghton et al., 2019; Bastani; Namavari, & Shaffer, 2019). However, the use of topic modeling for exploration of research topics in relation to the educational field is still limited.

To this end, the present study conducted a topic-based bibliometric analysis of the 3963 articles of *Computers & Education* during the period 1976–2018. The major research topics, their trends over time, their correlations, and their distributions across influential countries/regions and institutes, were analysed and presented. In addition, the major contributors to the *Computers & Education* , as well as the scientific collaborations among them, were identified and depicted for the first time. Specifically, this study focused on five major research questions:

(1) Which countries/regions and institutions were the major contributors to *Computers & Education*?
(2) What were the scientific collaborations among major contributors like?
(3) In what research topics were the *Computers & Education* community interested ?
(4) How did such research topics evolve over time?
(5) What were the main research concerns of the major contributors?

2. Dataset and method

A flowchart of the dataset acquisition and analysis methodology is depicted in Fig. 1. The overall scheme can be divided into three sub-processes: (i) data retrieval and pre-processing, (ii) structural topic modeling, and (iii) performance analysis. These sub-processes are elaborated in the following three sub-sections.

2.1. Data retrieval and preprocessing

The *Computers & Education* articles during the period 1976–2018 were retrieved from Web of Science, using the search strategy "Publication Name = *Computers & Education*." The results were then restricted to original research articles (Geng et al., 2017). A total of 3963 articles were retrieved. Citations of these articles were also retrieved up to July 06, 2019.

The primary materials of the topic modeling were the title, keywords, and abstract of each article. It is commonly agreed that titles, abstracts, and article keywords are suitable for conceptual reviews, because they usually represent the noteworthy content of articles (Cretchley, Rooney, & Gallois, 2010; Zhong, Geng, Liu, Gao, & Chen, 2016). In addition, abstracts are able to present summaries of articles in terms of research aims and problems, as well as major findings (Lee, Jung, & Song, 2016; Yan, 2015). Of the articles collected, 621 articles without abstracts were excluded, and 3342 articles with abstract information were selected for topic modeling analysis. The dataset, as well as the sources for the analysis codes, are available online.[2]

In the analysis of prolific countries/regions, articles affiliated to England, Scotland, Wales, and Northern Ireland were unified into articles of the UK. However, articles affiliated to Hong Kong, Macau, and Taiwan were individually calculated.

To improve the data quality before conducting the topic modeling, pre-processing was performed. Firstly, numbers, punctuation, symbols, and stop words (e.g., "me," "I," "or," "him," "a," and "they") were deleted to enhance consistency and reduce computational load (Boyd-Graber & Blei, 2009; Hoffman, Bach, & Blei, 2010). Secondly, terms with multiple spellings were consolidated (e.g., "behaviour" and "behaviour"). Thirdly, terms were converted to the singular form and lower case. We then assigned the weights 0.4, 0.4, and 0.2 to terms from keywords, titles, and abstracts, separately, as suggested by (Chen et al., 2018c). Since in topic modeling, the estimations of document-topic and topic-term distributions are based on the document-term distribution, which is frequency-based, the assignment of weights was performed by multiplying the frequency by weight. For example, for each document, if f_{1w_i},f_{2w_i},f_{3w_i} denoted the frequencies of word w_i amongst the keywords, titles, and abstracts respectively, then the weighted frequency of word w_i in the document was denoted by $0.4*f_{1w_i} + 0.4*f_{2w_i} + 0.2*f_{3w_i}$.

2.2. Structural topic modeling

To identify the topics of the 3342 articles with abstract information, we employed a newly developed topic modeling method, the structural topic modeling (STM) (Roberts, Stewart, & Tingley, 2014; Roberts et al., 2014). The graphical representation map for topic modeling, adapted from Nabli, Djemaa, and Amor (2018), is shown in Fig. 2. Topic modeling considers each document as being composed of terms, each topic as a distribution over terms, and each document as a combination of topics. Given K topics for the d^{th} document and V terms for the k^{th} topic, STM performs two major tasks toward estimating the distributions of the document-topic θ_d and the topic-term β_k. A variational expectation maximization (VEM) method was applied to the estimation of parameters (Roberts, Stewart, & Airoldi, 2016).

Although STM is relatively new, applications of it in topic detecting research are common. For example, Reich, Tingley, Leder-Luis, Roberts, and Stewart (2015) adopted STM to uncover topics hidden in discussion forum posts of an online course. Tvinnereim and Fløttum (2015) implemented STM to explore people's understanding of climate change. By utilizing STM, Das, Dixon, Sun, Dutta, and Zupancich (2017) identified the research themes discussed in transportation articles. Their study demonstrated that STM enabled the creation of tools for investigating the topic prevalence and relevant trends in the research.

In this study, an R package, named *stm* (Roberts, Stewart, & Tingley, 2014) was utilized. STM is an unsupervised modeling method, one essential step of which is to decide upon the number of topics before modeling. Existing research work demonstrated that an exclusive reliance on statistical measures could result in a less meaningful model parameter choice (Levy & Franklin, 2014). Thus, following the suggestions of previous studies (Farrell, 2016; Tvinnereim & Fløttum, 2015), we ran a set of models by setting topic numbers as 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, and 35. Two domain experts independently compared the 16 models with different numbers of topics by inspecting the representative terms and articles (Jiang, Qiang, Fan, & Zhang, 2018), based on the following criteria.

(1) Representative terms in each topic could form a meaningful topic together;
(2) The top representative articles for each topic were in close relation to the topic;
(3) There was no overlap between topics within one topic model;
(4) All important topics in educational technology were included.

Based on the above criteria, the two domain experts independantly selected the best fitting model. It turned out that they both selected the 24-topic model. The 24-topic model was identifiedsince qualitative evaluation also indicated that this number produced the greatest semantic consistency within topics, as well as exclusivity between topics.

To illustrate the robustness over topics, an analysis of the 24-topic estimation was compared against the estimations with fewer

[2] https://drive.google.com/file/d/1-jdYiDp6DWFOfsjN4tfaJWzkxQGuI5hi/view?usp=sharing.

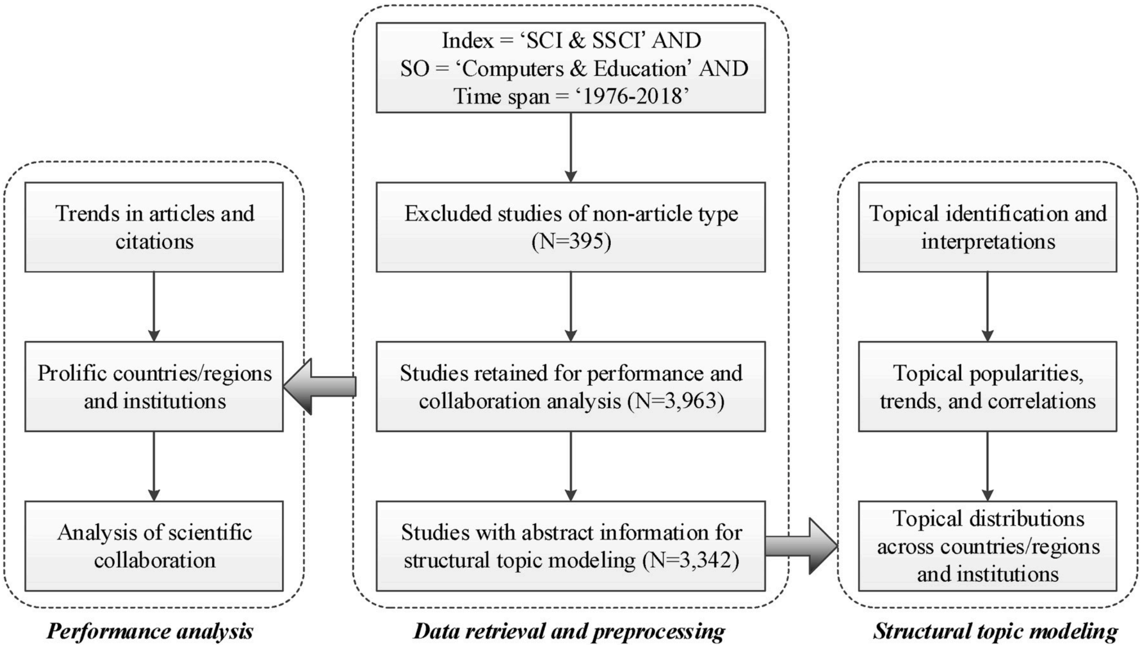

Fig. 1. The flowchart of the dataset acquisition and analysis methodology.

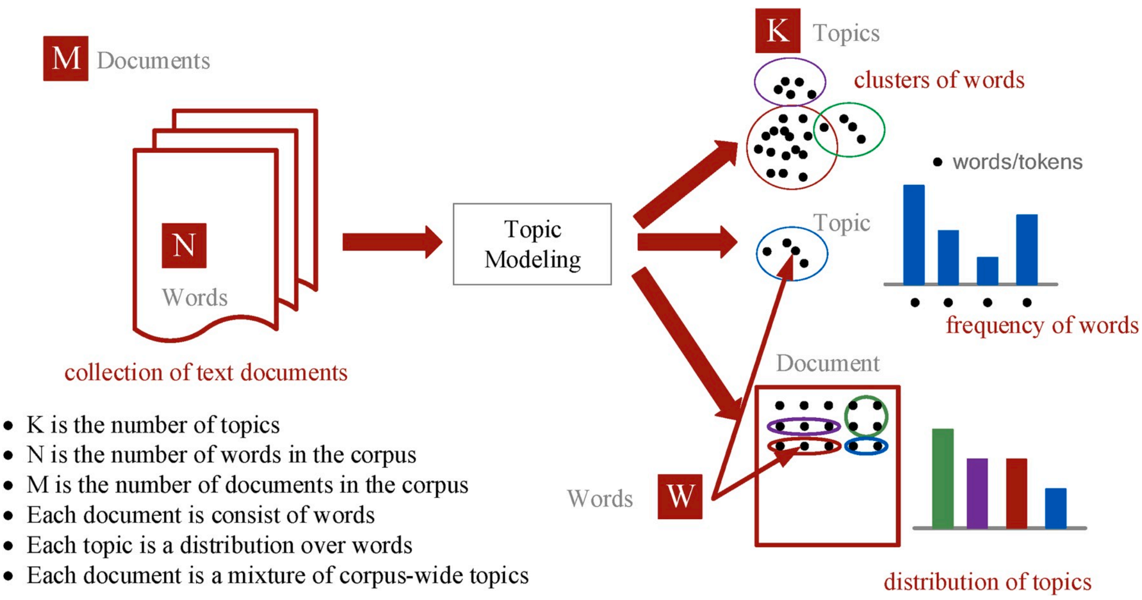

Fig. 2. Graphical representation map for topic modeling (adapted from Nabli, Djemaa, and Amor, 2018).

topics (e.g., K = 23) and more topics (e.g., K = 25). Table 2 shows the comparisons between the 23-, 24-, and 25-topic models.

The problem of using fewer than 24 topics was that meaningful research issues were confounded. For example, in the 23-topic estimation, as shown in Table S1 in the Supplementary materials, *Human–computer interaction* and *Virtual reality* were combined into one topic. Compared to the 24-topic model, in the 25-topic model (see Table S2 in the Supplementary materials), the topics *Human–computer interaction* and *Program and curriculum* were abstent, and the topics *Evaluation and organization*, *Communication channels*, and *Teaching methods* appeared. As human–computer interaction had gradually evolved into an established field of teaching and research (Gross, 2014), it had been a broadly studied and essential issue in educational technology, and as such it could not be overlooked. Thus, we finalized the input by selecting the 24-topic model, as it captured all major research issues in the field of computers and education.

Table 2
The comparison of the 23-, 24-, and 25-topic models.

Labels for the 23-topic model	Labels for the 24-topic model	Labels for the 25-topic model
Online/web-based learning	*Online/web-based learning*	*Online/web-based learning*
Blended learning	*Blended learning*	*Blended learning*
Technology acceptance model	*Technology acceptance model*	*Technology acceptance model*
Special education	*Special education*	*Special education*
Context learning and collaborative learning	*Context learning and collaborative learning*	*Context learning and collaborative learning*
Demographic issues	*Demographic issues*	*Demographic issues*
Program and curriculum	*Program and curriculum*	*Teaching methods*
Data mining	*Data mining*	*Data mining*
Assessment	*Assessment*	*Assessment*
Mobile learning and early childhood education	*Mobile learning and early childhood education*	*Mobile learning and early childhood education*
Massive open online courses	*Massive open online courses*	*Massive open online courses*
Social networks and communities	*Social networks and communities*	*Social networks and communities*
Science education	*Science education*	*Science education*
E-learning and Policy	*E-learning and policy*	*E-learning and policy*
Hardware	*Hardware*	*Hardware*
Teacher training	*Teacher training*	*Teacher training*
Language learning	*Language learning*	*Language learning*
Conceptual mapping	*Conceptual mapping*	*Conceptual mapping*
Multimedia and data-driven	*Multimedia and data-driven*	*Multimedia and data-driven*
Experiments and methodologies	*Experiments and methodologies*	*Experiments and methodologies*
Game-based learning	*Game-based learning*	*Game-based learning*
Human-computer interaction and Virtual reality	*Virtual reality*	*Virtual reality*
Programming language	*Programming language*	*Programming language*
	Human-computer interaction	*Evaluation and organization*
		Communication channels

2.3. Analysis of STM results

The analyses of the model results included topics' interpretations, proportions, trends, and correlations, as well as their distribution across influential countries/regions and institutions. We first interpreted the statistical results into important topics relevant to the field of computer- or technology-enhanced education. We then obtained the most discriminating terms for each of the topics based on a distribution matrix of topics and terms (Roberts et al., 2016). The label for each topic was identified and summarized by two domain experts. Specifically, the following steps were set for conducting the labeling task.

(1) Interpretation of the discriminating terms within topics based on their semantic meanings;
(2) Examination of a sample of representative articles for each of the topics;
(3) Comparison of the labeling results of the two experts, with the inconsistent labels being discussed and unified.

Take the topic *Context learning & Collaborative learning* as an example. The two domain experts first examined the most representative terms such as "collaborative," "cooperative," "collaboration," "context-aware," and "computer-supported collaborative learning (CSCL)" and found that they were all context- or collaboration-related. Next, they examined the three most representative articles for this topic, details of which are presented as follows. (1) Splichal, Oshima, and Oshima (2018) developed and evaluated a computer-based collaborative learning setting for project-enhanced learning . (2) Hwang, Chu, Lin, and Tsai (2011) explored how Mindtool could support students' learning with a context-aware ubiquitous learning process and compared it to learning with a conventional ubiquitous learning process. (3) Hwang, Wang, and Sharples (2007) evaluated the use and influence of a web-based annotation application in online learning, with the employment of collaborative mechanisms of group and full annotation-sharing to enhance learners' annotation motivation. The first and third articles were related to collaborative learning, while the second related to context learning. The two domain experts discussed with each other; based on the examination results of the representative terms and articles, and named the topic *Context learning & Collaborative learning*. For the topic *Online/web-based learning*, the two domain experts first inspected the discriminating terms such as "podcasting," "distance," "tele-learning," "medium," "podcast," and "computer-mediated," which pertained to online/web services, as well as terms such as "post-secondary," "education," "teaching-learning," "higher," "university," and "institutional," which were education- or learning-related. Then, they examined the top three representative articles of *Online/web-based learning* to verify the label. These are as follows. (1) Shneiderman (1998) published an article concerning a teaching or learning philosophy for cyber-generation. (2) Walls et al. (2010) investigated learners' readiness and attitudes towards tedious and supplementary podcasting. (3) Beyth-Marom, Chajut, Roccas, and Sagiv (2003) examined differences in terms of demographics, achievements, and value priorities between learning in internet-based and traditional distance-learning environments. The aforementioned three all related to learning using cyber, podcasting, internet, and distance services, all of which could be considered as online/web-based learning. Thus, considering the representative terms and research work, we labelled the topic *Online/web-based learning*. Following the same strategy, welabelled the other 22 topics.

Next, to investigate the popularity and prevalence of each topic in the computer- or technology-enhanced education research, we calculated topics' proportions based on a θ matrix estimated by STM, where θ_{ij} ($i = 1, 2, \ldots, 3324 j = 1, 2, \ldots 24$) was the probability of article i being assigned to topic$j$. Since an article could be related to more than one topic, we considered the probability of each article to each topic, rather than selecting only the topic with the highest proportion. For instance, in a four-topic model, one document might be 55% related to Topic 1 and 15% to each of Topics 2, 3, and 4. Thus, in this study, for article i, its proportions over all the 24 topics were denoted as $\theta_{i,1}$ $\theta_{i,2}$, …, and $\theta_{i,24}$, respectively, where $\theta_{i,1}+\theta_{i,2}+\ldots+\theta_{i,24}=1$. For topic j, the proportions were denoted $\theta_{1,j}\theta_{2,j}$, …, and $\theta_{3324,j}$, respectively. Thus, to indicate how popular each topic was, we summed the proportions of each article by topic to obtain the proportions for each topic, that is, $\theta_{1,j}+\theta_{2,j}+\ldots+\theta_{3324,j}$. To investigate if the identified topics exhibited increasing or decreasing trends, we applied the Mann-Kendall statistical test (Mann, 1945). We employed an R package called *huge* (Zhao, Liu, Roeder, Lafferty, & Wasserman, 2012) to indicate how the topics correlated to each other, which visually displayed correlations based on a semi-parametric Gaussian procedure. In the graph, each topic was represented by a circle, with the size being proportional to the topic's proportion. Topics connected by a dotted line were more likely to be discussed within a paper. A shorter link between two topics indicated a stronger correlation between the two.

Moreover, we identified and compared the topic distributions for prolific countries/regions and institutions. Using the topic proportion metric of prolific countries/regions (or institutions) in json format as the dataset, we implemented a graphing tool named Cluster Purity Visualizer (Swamy, 2016) to obtain a basic distribution graph. Using JavaScript packages d3.v3.js[3] and clusterpurityChart.js,[4] the basic graph was then modified to conduct layout adjustment and coloring.

3. Results

The results of our analyses are displayed, presenting article and citation trends and analyses of prolific countries/regions and institutions, together with the analyses of the topical identifications, trends, correlations, and distributions across prolific countries/regions and institutions.

3.1. Analyses of the trends of the article and citation counts

The year-by-year trends of the article and citation counts are depicted in Fig. 3. The numbers of the *Computers & Education* articles that were published annually generally showed an increasing trend. Before 2006, the number of articles published annually was quite low, around 60. From 2006 to 2008, the annual number of *Computers & Education* articles increased fourfold, i.e., to about 240, then the number remained in fluctuation until 2015. In the following years, the number had a slight decline. Overall, *Computers & Education* had received a growing interest from the academic community.

Regarding citations, the number of annual citations of the 3342 articles exhibited a continually increasing trend. Such results demonstrated the growing influence and impact of *Computers & Education* in academia. Until 2004, the annual number of citations was comparatively low, remaining below 350. Since then, this number seemed to have grown exponentially, reaching a peak of 14,972 in 2017. The slight drop observed in the citation count for the most recent year (2018) might result from the citation time-window. From this, it is reasonable to predict that the annual number of citations will continue to increase in future.

3.2. Prolific countries/regions and institutions

In the analyses concerning countries/regions and institutions, all the countries/regions and institutions contributing to each article were included in the data, and the most prolific ones were evaluated using three bibliometric indicators: TP for article count, TC for citation count, and H for Hirsch index. These analyses were a continuation of the study by Chen et al. (2019c), which reported the top influential countries and institutions, as measured by the Hirsch index.

A total of 85 countries/regions contributed to the 3963 articles comprising the *Computers & Education* corpus. Despite of the large geographic distribution of the article contributors, the top 11 countries/regions ranked by the article count in Table 3 together contributed to more than 73% of the 3963 articles. In terms of the Hirsch index, the USA (78), Taiwan (76), the UK (56), Spain (43), and the Netherlands (41) were the top five countries/regions. It is worth noting that although Taiwan contributed far fewer articles than the USA, its Hirsch index value was very close to that of the USA. This showed the wide influences of the articles published by academics affiliated with Taiwan institutions in *Computers & Education*.

Table 4 displays the 15 most prolific institutions. These institutions altogether contributed to nearly 20% of the total corpus. Among these 15, eight were from Taiwan; and three of the top four were also from Taiwan, demonstrating the dominant position of the publications by institutions from Taiwan in the community of *Computers & Education*. *National Taiwan Normal University* contributed the most (92 articles), followed by *The Open University* from the UK (83), *National Taiwan University of Science and Technology* from Taiwan (73), and *National Central University* from Taiwan (63). In terms of the Hirsch index, *National Taiwan University of Science and Technology*, *National Taiwan Normal University*, and *National Central University* were the top three institutions. *National Taiwan University of Science and Technology*, though exhibiting a relatively low article count as compared to *National Taiwan Normal University*, had a much higher Hirsch index value. This demonstrated the wide influences of the *Computers & Education* articles contributed by *National Taiwan University of Science and Technology*.

[3] https://d3js.org/d3.v3.js.

[4] https://bl.ocks.org/nswamy14/raw/e28ec2c438e9e8bd302f/clusterpurityChart.js.

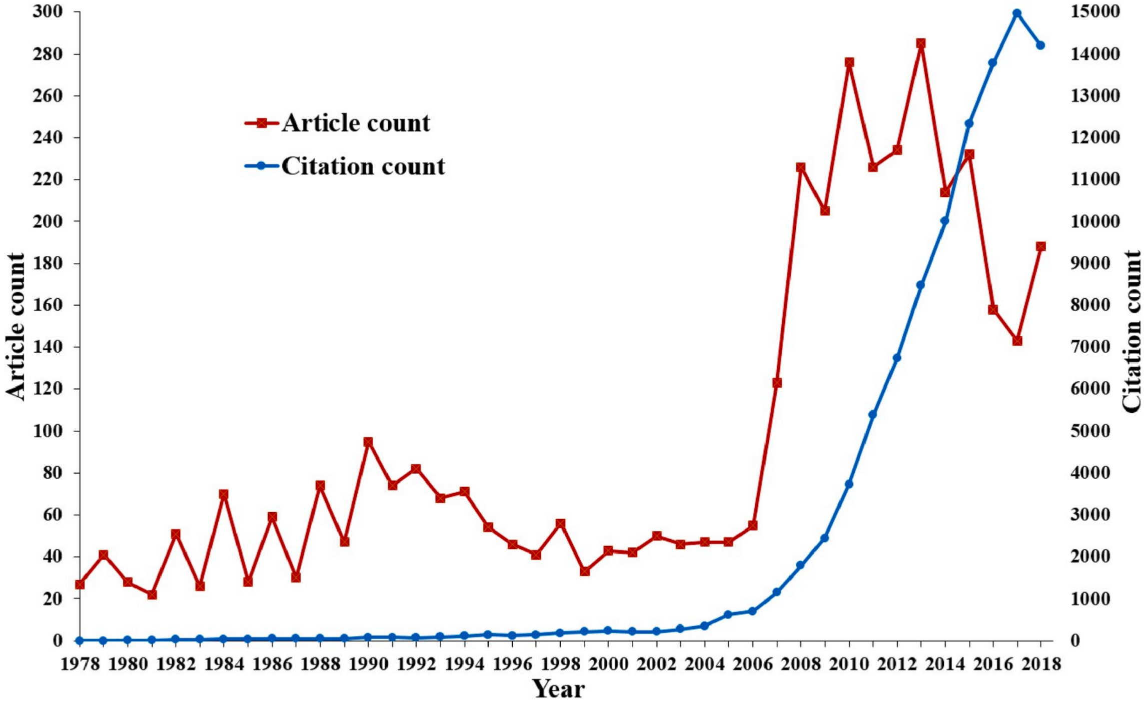

Fig. 3. Year-by-year analyses of the article and citation counts.

Table 3
Top countries/regions ranked by the article count.

Country/Region	TP	TC (R)	H (R)
USA	858	24891 (1)	78 (1)
UK	736	13378 (3)	56 (3)
Taiwan	534	20964 (2)	76 (2)
Spain	210	7288 (4)	43 (4)
Netherlands	205	5910 (5)	41 (5)
Canada	199	3723 (8)	32 (9)
Australia	182	4763 (6)	34 (7)
Turkey	117	3679 (9)	34 (7)
Germany	111	2208 (13)	26 (12)
Greece	90	3878 (7)	35 (6)
Hong Kong	90	2679 (12)	28 (11)

AbbreviationsTP: article count; TC: citation count; H: Hirsch index.

3.3. Analysis of the scientific collaborations

The collaborative scientific research relationships among the prolific countries/regions and institutions were visualized through social network analysis using Gephi[5] (Bastian, Heymann, & Jacomy, 2009). Different from Chen et al. (2019c) which reported scientific collaborations amongst prolific authors, the present research focused on the collaborations among countries/regions and institutions. In the network, countries/regions and institutions were represented by nodes. The size of each node denoted the article count of each country/region or institution. The various forms of groupings were colored differently according to continental or national/regional information.

The collaborative network connecting the top 20 most prolific countries/regions is shown in Fig. 4, including 95 links and 20 nodes. Of these 20 countries/regions, the USA, the UK, Taiwan, and Germany collaborated with the most countries/regions, each with 17, 15, 14, and 14 respectively. The USA and Taiwan had the biggest number of collaborations (34 articles), followed by the USA and China (20), the USA and South Korea (19), and the USA and Canada (14).

The collaborative scientific research relationships among the top 20 most prolific institutions are illustrated in Fig. 5, which includes 20 nodes and 43 links. Of these 20 institutions, *National Taiwan University of Science and Technology*, *National Central University*,

[5] https://gephi.org/.

Table 4
Top institutions ranked by the article count.

Institution	Country/Region	TP	TC (R)	H (R)
National Taiwan Normal University	Taiwan	92	2528 (3)	29 (2)
The Open University	UK	83	2090 (7)	23 (7)
National Taiwan University of Science and Technology	Taiwan	73	4503 (1)	39 (1)
National Central University	Taiwan	63	2687 (2)	27 (3)
Nanyang Technological University	Singapore	56	2418 (4)	27 (3)
University of Twente	Netherlands	52	1623 (9)	19 (11)
National Chiao Tung University	Taiwan	51	1623 (9)	21 (10)
National Cheng Kung University	Taiwan	49	1838 (8)	23 (7)
University of Ghent	Belgium	43	2100 (6)	24 (6)
National Sun Yat-Sen University	Taiwan	41	1530 (12)	22 (9)
University College London	UK	40	1226 (14)	17 (13)
The University of Hong Kong	Hong Kong	36	903 (27)	17 (13)
National University of Tainan	Taiwan	35	2223 (5)	25 (5)
Utrecht University	Netherlands	31	775 (28)	14 (17)
National Changhua University of Education	Taiwan	28	1010 (25)	15 (16)

Abbreviations: TP: article count; TC: citation count; H: Hirsch index.

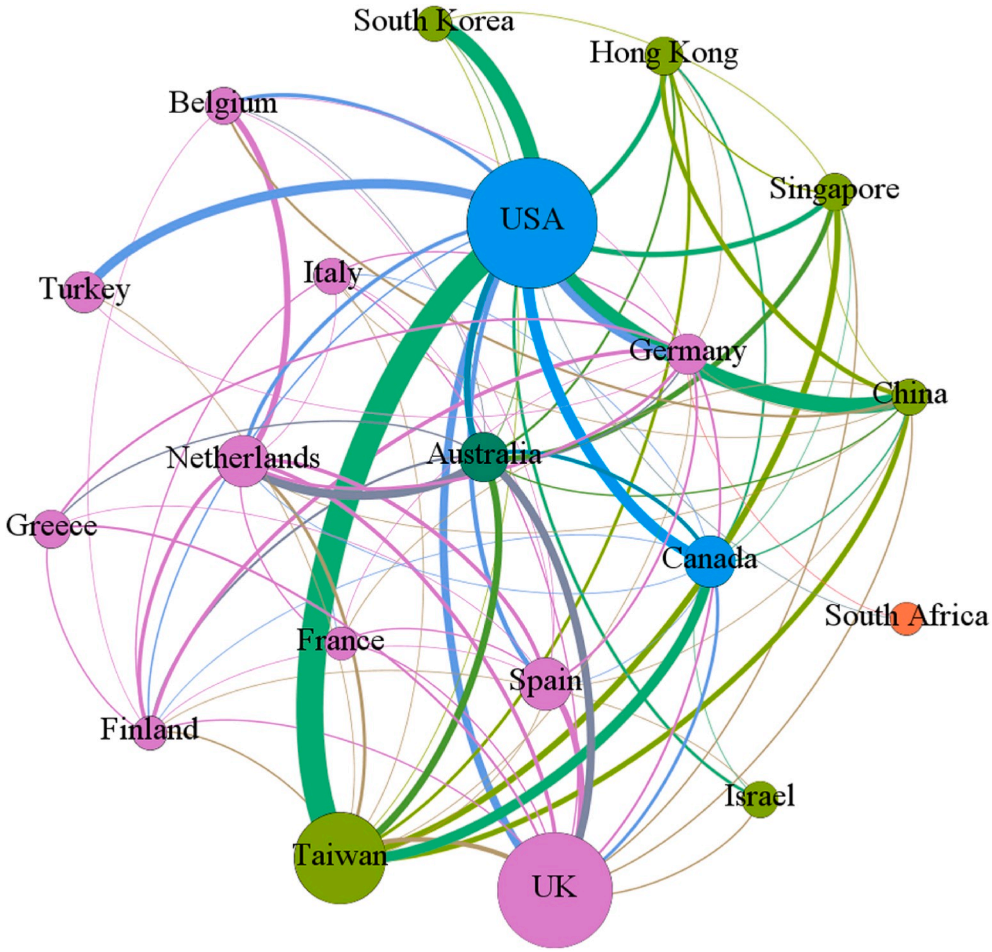

Fig. 4. Collaborations among the top 20 prolific countries/regions.

National Taiwan Normal University, and *National Changhua University of Education* were the most collaborative. All of them were Taiwanese. These institutions had collaborated with ten, nine, seven, and seven other institutions, respectively. The majority of the institutions in the network were located in Taiwan (pink nodes), and the collaborations within this group were very close. *National Taiwan Normal University* and *National University of Tainan* published the largest number of collaborative articles (14), followed by

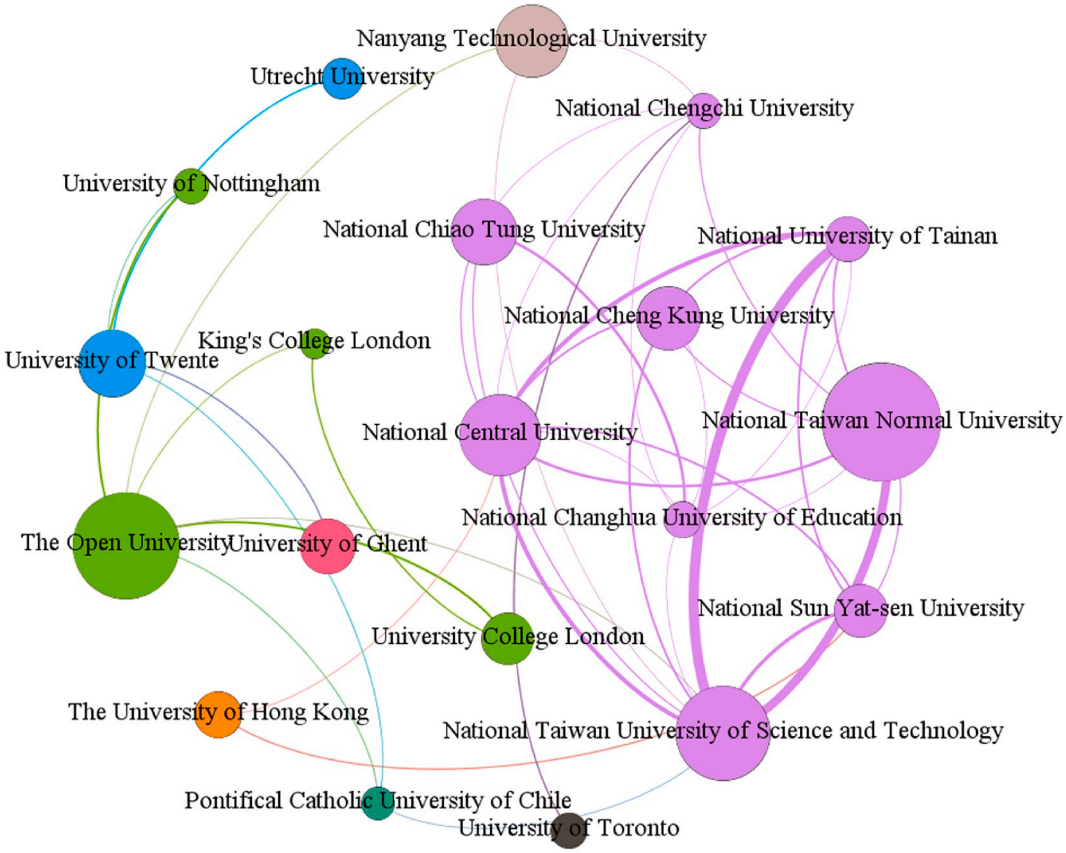

Fig. 5. Collaborations among the top 20 prolific institutions.

National Taiwan Normal University and *National Taiwan University of Science and Technology* (12).

3.4. Topic identification, trends, and correlations

The results of the STM analysis showed that the most frequently used terms in the 3342 articles included "learning (in 2500 articles)," "student (2351)," "education (1840)," "environment (1450)," "technology (1355)," "system (1256)," and "computer (1099)." As stated by Grimmer and Stewart (2013), the key methodological point is to "validate, validate, and validate." Thus, we further implemented three other topic-modeling approaches including latent Dirichlet allocation (LDA) (Blei, Ng, & Jordan, 2003) using VEM, Gibbs sampling, and latent semantic analysis (LSA) to verify the results. The 24-topic model showed the best fitting performance, and the interpretations of the 24 topics for the four methods were approximately identical, as exemplified and demonstrated in Table 5. For instance, regarding the topic *Game-based learning*, several game-related terms such as "game," "gaming," "gameplay," "gamification," "play," "game-based," and "playing," appeared consistently across the four topic models. As for the topic *Technology acceptance model*, the four methods all identified terms such as "acceptance," "perceived," "technology,""satisfaction," and "usefulness". For the topic *Assessment*, several assessment-related terms such as "peer-assessment," "e-assessment," "self-assessment," "assessment," and "feedback," were identified by the four models. Thus, using triangulation, we selected the 24-topic model for the exploration of the research topics and topic trends within *Computers & Education* publications.

Table 6 shows the 24-topic STM results, with the representative terms, topics' proportions within the whole corpus, suggested topic labels, and topical trends. The top five most-discussed topics were *Context and collaborative learning* (7.49%), *E-learning and policy* (6.61%), *Experiments and methodologies* (6.01%), *Human–computer interaction* (5.31%), and *Social network and communities* (5.19%).

Note: Topics are ranked by proportion in a descending order. Abbreviations are displayed in Table S3 in Supplementary materials. ↑(↓): increasing (decreasing) trend but not significant ($p > 0.05$); ↑↑(↓↓), ↑↑↑(↓↓↓), ↑↑↑↑(↓↓↓↓): significantly increasing (decreasing) trend ($p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

From the results of the Mann-Kendall test, it can be seen that 13 topics, *Context and collaborative learning, E-learning and policy, Experiments and methodologies, Social networks and communities, Blended learning, Online/web-based learning, Multimedia and data-driven studies, Technology acceptance models, Mobile learning and early childhood education, Game-based learning, Teacher training, Language learning*, and *Assessment*, demonstrated significantly increasing trends. On the other hand, eight topics, *Human–computer interaction, Program and curriculum, Data-mining, Massive open online courses (MOOCs), Conceptual mapping, Programming language, Special*

Table 5
Interpretations of the topics fitted using STM, VEM, Gibbs sampling, and LSA.

Game-based learning	
STM	game, serious, game-based, gameplay, videogame, gbl, mmorpg, multiplayer, in-game, gaming, leaderboard, playing, player, dgbl, competition
VEM	game, learning, motivation, serious, play, game-based, educational, computer, video, gaming, student, design, environment, education, digital
Gibbs sampling	game, motivation, engagement, video, educational, performance, study, result, serious, design, game-based, impact, play, gaming, gamification
LSA	game, school, child, digital, gameplay, computer, video, motivation, playing, educational, gaming, gender, play, skill, simulation
Technology acceptance model	
STM	acceptance, continuance, tam, intention, perceived, adoption, usefulness, information-technology, ease, e-learning, satisfaction, lms, equation, structural, antecedent
VEM	perceived, model, acceptance, technology, use, intention, factor, self-efficacy, user, learning, study, satisfaction, usefulness, adoption, usage
Gibbs sampling	model, e-learning, perceived, use, acceptance, technology, factor, user, intention, satisfaction, influence, adoption, usefulness, theory, usage
LSA	acceptance, model, perceived, intention, technology, mobile, user, self, usefulness, learning, web, use, ease, attitude, adoption
Assessment	
STM	peer-assessment, feedback, formative, assessment, e-assessment, portfolio, peer, self-assessment, e-portfolio, caf, assessor, summative, quiz, gpam-wata, wata
VEM	assessment, feedback, student, peer, writing, formative, system, study, question, learning, response, portfolio, performance, web-based, result
Gibbs sampling	student, assessment, problem, feedback, peer, question, response, solving, formative, problem-solving, performance, type, computer-based, web-based, answer
LSA	assessment, teacher, feedback, peer, online, formative, service, game, pre, classroom, self, portfolio, knowledge, tpack, student
Virtual reality	
STM	vr, reality, web3d, ar, virtual, scorm, augmented, object, museum, metaphor, world, visitor, immersive, adaptation, oscar
VEM	virtual, environment, learning, reality, education, presence, laboratory, student, interactive, world, augmented, simulation, experience, life, teaching
Gibbs sampling	environment, virtual, simulation, education, interactive, learning, reality, world, application, reserved, experience, right, interaction, augmented
LSA	virtual, programming, social, reality, mobile, self, environment, problem, solving, teacher, internet, feedback, child, community, efficacy
Language learning	
STM	e-book, efl, dictionary, spelling, print, phonological, reading, English, writing, book, foreign, reader, vocabulary, storybook, handwriting
VEM	language, English, reading, vocabulary, learner, comprehension, annotation, student, text, music, word, study, foreign, story, learning
Gibbs sampling	language, reading, writing, English, comprehension, text, learner, electronic, student, vocabulary, word, source, hypertext, study
LSA	reading, programming, language, online, literacy, child, vocabulary, learner, community, comprehension, writing, digital, English, text, reader

Note: Abbreviations are displayed in Table S3 in Supplementary materials.

education, and *Hardware*, showed significantly decreasing trends. The remaining three topics, i.e., *Demographic issues*, *Virtual Reality*, and *Science education,* showed no significantly increasing or decreasing trend. The annual proportions of the identified topics are also visualized in Fig. 6. These analyses were a continuation of the study by Chen et al. (2019c) which reported the top frequently used keywords and visualized their annual trends. However, in this study, we focused on the evolution of the topics identified using a topic model.

The layout of topic correlations, based on a semi-parametric Gaussian procedure, is shown in Fig. 7. In the figure, a shorter link between two topics indicated a stronger correlation between them. For example, close links among *Social network and communities*, *Online/web-based learning*, and *Blended learning* are presented.

3.5. Topic distributions of the prolific countries/regions and institutions and the annual topic distributions

The topic distributions of the prolific countries/regions and institutions are visualized in Fig. 8, which shows a clear picture of which countries/regions or institutions were productive in, and devoted to, particular topics. For example, the UK was more active in *Program and curriculum*, while Turkey was more interested in *Experiments and methodologies*. *National Taiwan University of Science and Technology* and *National Central University* were more productive in *Context and collaborative learning*, while the *University of Twente* and *University of Ghent* had contributed more to *E-learning and policy*.

Fig. 9 shows the topic proportion distributions by year in the *Computers & Education* publications. The results clearly showed the dominating research topics for each year. For example, *Programming language* was the most focused-upon topic in 1991, and *Program and curriculum* gained the most attention from the *Computers & Education* community in 1992. In 1993, *Conceptual mapping* was the predominant focus of the community. *Hardware* was the most-studied issue in 1994. These results also showed that in earlier years, authors tended to concentrate more on a handful of specific research topics, whereas in the later years, the community seemed to have paid more balanced attention to almost every prominent aspect of research.

Table 6
Discriminating terms, their proportions in the whole corpus, suggested topic labels, and developmental trends.

Representative terms	%	Labels	*Trend*	*p*
collaborative, cooperative, collaboration, orchestration, computer-supported, context-aware, learning, blended, script, ubiquitous, cscl, learner, environment, reflective, activity	7.49	*Context and collaborative learning*	↑↑↑	0.0019
ict, teacher, blogging, integration, pre-service, policy, competence, blog, digital, barrier, competency, in-service, school, professional, secondary	6.61	*E-learning and policy*	↑↑↑↑	0.0005
group, experimental, instruction, improving, mathematics, post-test, elementary, achievement, classroom, pre-test, effectiveness, control, powerpoint, class, intervention	6.01	*Experiments and methodologies*	↑↑↑↑	0.0000
evaluation, web, methodology, cal, design, educational, interface, usability, evaluating, guideline, criterion, human-computer, software, application, site	5.31	*Human-computer interaction*	↓↓↓↓	0.0003
community, cmc, synchronous, discussion, asynchronous, presence, message, discourse, forum, social, networking, exchange, participation, twitter, computer-mediated	5.19	*Social networks and communities*	↑↑↑↑	0.0002
resource, courseware, teaching, program, staff, module, cbl, trainee, webquest, material, training, faculty, webcasting, dialogic, workshop	5.13	*Program and curriculum*	↓↓↓↓	0.0000
girl, gender, internet, female, male, anxiety, boy, adolescent, attitude, parenting, home, self-efficacy, inequality, problematic, parental	4.62	*Demographic issues*	↓	0.6495
multitasking, laptop, engagement, academic, self-regulation, clicker, exam, flipped, distraction, attendance, gamification, badge, self-regulated, srl, achievement	4.29	*Blended learning*	↑↑↑↑	0.0000
neural, adaptive, mining, fuzzy, personalized, Bayesian, classification, automatic, prediction, diagnostic, algorithm, intelligent, grading, cat, testing	4.29	*Data mining*	↓↓	0.0135
podcasting, distance, post-secondary, telelearning, medium, podcast, education, teaching-learning, higher, university, preference, computer-mediated, goal, orientation, institutional	4.29	*Online/web-based learning*	↑↑	0.0345
load, animation, cognitive-load, narration, split-attention, spatial, cognitive, self-explanation, static, visual, multimedia, presentation, picture, eye, visualization	4.27	*Multimedia and data-driven studies*	↑↑↑↑	0.0000
acceptance, continuance, tam, intention, perceived, adoption, usefulness, information-technology, ease, e-learning, satisfaction, lms, equation, structural, antecedent	4.25	*Technology acceptance model*	↑↑↑↑	0.0000
moocs, computing, dropout, massive, e-mail, career, delivery, course, lecturer, open, postgraduate, note, undergraduate, ocw, mail	4.16	*Massive open online courses*	↓↓↓↓	0.0000
map, hypertext, concept, hypermedia, representation, mapping, conceptual, domain, expertise, medical, navigation, fraction, modeling, expert, mental	3.65	*Conceptual mapping*	↓↓↓↓	0.0000
vr, reality, web3d, ar, virtual, scorm, augmented, object, museum, metaphor, world, visitor, immersive, adaptation, oscar	3.61	*Virtual reality*	↑	0.2601
programming, solving, recursion, problem, problem-solving, robotics, robot, solve, scratch, solution, computational, object-oriented, graph, debugging, novice	3.44	*Programming language*	↓↓↓↓	0.0000
mobile, device, phone, cross-cultural, app, tablet, ipad, handheld, pupil, parent, preschool, cultural, m-learning, informal, tel	3.36	*Mobile learning and early childhood education*	↑↑	0.0208
game, serious, game-based, gameplay, videogame, gbl, mmorpg, multiplayer, in-game, gaming, leaderboard, playing, player, dgbl, competition	3.08	*Game-based learning*	↑↑↑↑	0.0000
simulation-based, argumentation, scientific, scaffolding, chemistry, simulation, team, inquiry, creativity, project-based, after-school, teamwork, creative, scaffold, mentoring	2.96	*Science education*	↑	0.5402
tpack, instrument, agent, pedagogical, epistemic, epistemological, validity, scale, reliability, validation, technological, item, measurement, content, measuring	2.95	*Teacher training*	↑↑↑↑	0.0000
e-book, efl, dictionary, spelling, print, phonological, reading, english, writing, book, foreign, reader, vocabulary, storybook, handwriting	2.83	*Language learning*	↑↑	0.0283
autism, asd, geometry, disorder, spectrum, autistic, reasoning, bubble, geometric, tool, portal, child, story, mathematical, authoring	2.75	*Special education*	↓↓↓	0.0017
peer-assessment, feedback, formative, assessment, e-assessment, portfolio, peer, self-assessment, e-portfolio, caf, assessor, summative, quiz, gpam-wata, wata	2.74	*Assessment*	↑↑↑↑	0.0001
remote, music, bullying, cad, virtualization, laboratory, cyber, security, package, lab, electrical, engineering, spreadsheet, hands-on, hardware	2.70	*Hardware*	↓↓↓↓	0.0000

4. Discussion

4.1. The most representative research work for each topic

For a profound understanding of the identified topics, we analyzed the most-cited research work for each topic here. For the topic *Context and collaborative learning*, Zurita and Nussbaum (2004) explored how several issues, for example, the inconvenience of co-ordination and communication, difficulty of material organization, and mobility deficiencies, could be solved within a mobile, computer-enhanced collaborative learning environment. For the topic *E-learning and policy*, Pelgrum (2001) reported findings from an investigation of primary and secondary sectors to understand the major obstacles impeding ICT integration in schools. For *Experiments and methodologies*, by adopting an experimental design method, Kebritchi, Hirumi, and Bai (2010) aimed to discover how computer games affected the achievement and motivation of mathematics learners. For *Human–computer interaction,* through an examination of secondary school students, Walraven, Brand-Gruwel, and Boshuizen (2009) found that students seldom evaluated the information they found online. For *Social network and communities,* using social constructivist learning as their research framework, Pena-Shaff and Nicholls (2004) examined communication forms and knowledge construction processes of learners utilizing a computer bulletin board system for course discussion. For *Program and curriculum*, using activity theory as a basis, Blin and Munro (2008) presented discussions concerning their preliminary analysis of the teaching practices revolution. For *Demographic issues,* Li and Kirkup (2007) examined the

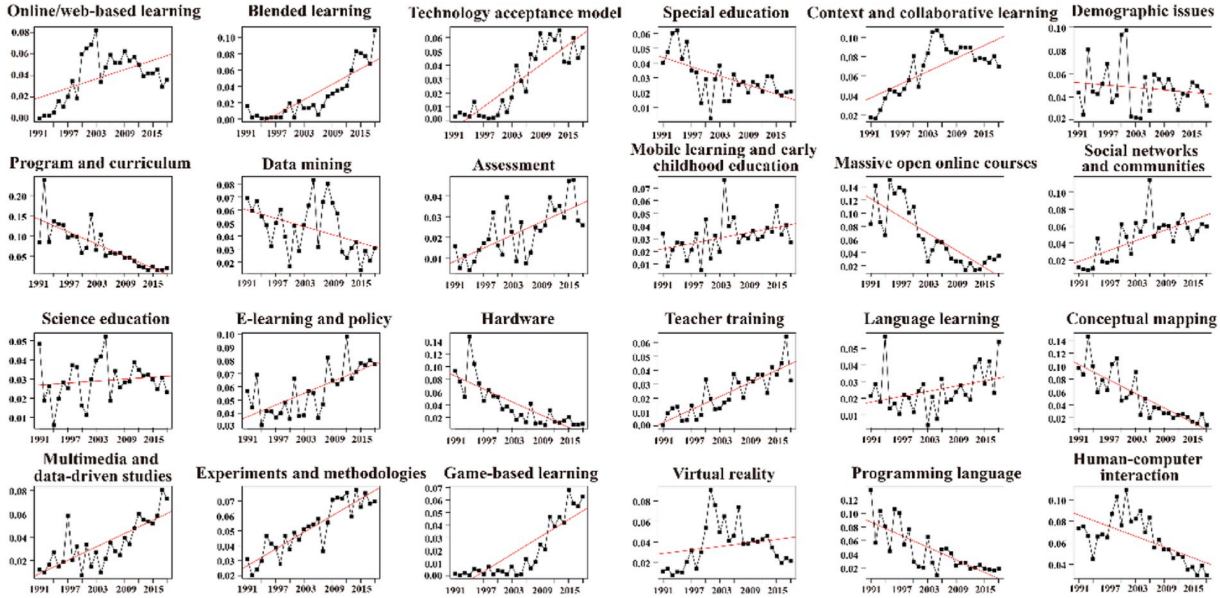

Fig. 6. Annual topic proportion within the whole corpus for the 24 topics.

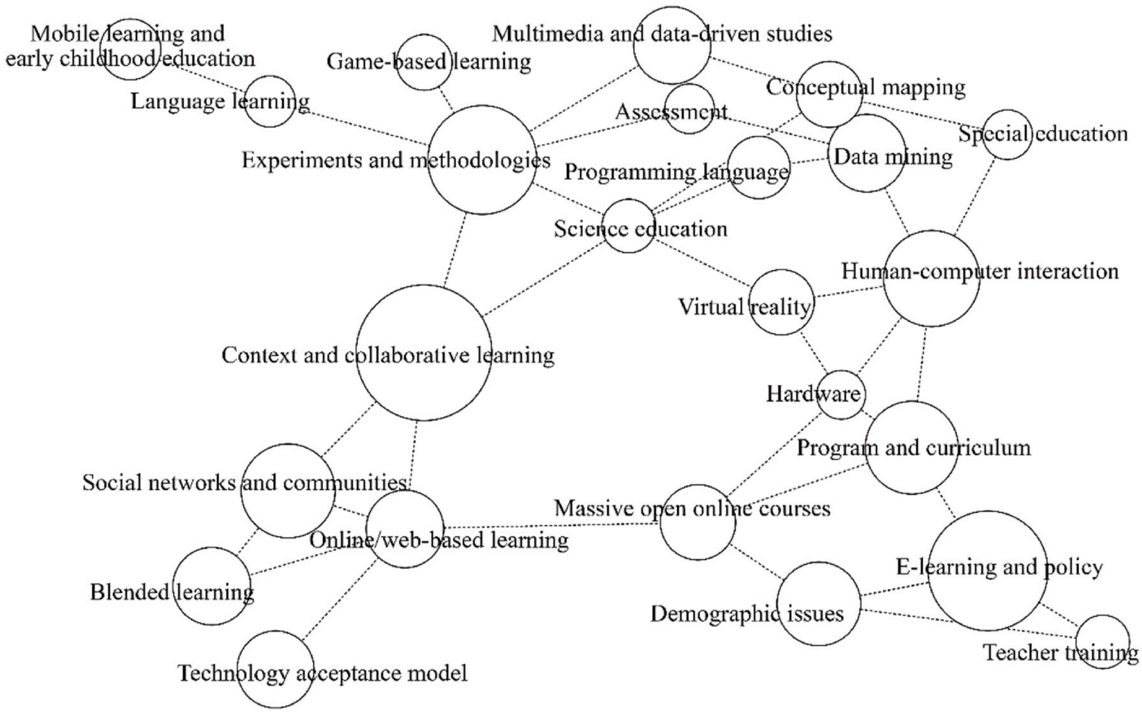

Fig. 7. Graphed positive correlations between the 24 topics.

differences between Chinese and British learners in their use of, and attitudes towards, computers and the Internet. In addition, they investigated the gender differences within this context. For *Blended learning,* Junco (2012) investigated how learners' Facebook use frequencies and activity participation related to their engagement. For *Data mining*, Romero, Ventura, and García (2008) first surveyed the adoption of data mining technologies in learning management systems, and then provided a tutorial using Moodle. For *Online/-web-based learning,* Jones, Ramanau, Cross, and Healing (2010) reported the major findings from the first period of a project exploring online learning of net generation-age college students. For *Multimedia and data-driven studies*, Mason, Tornatora, and Pluchino (2013) adopted eye-tracking techniques to explore how students processed texts and graphics online during the process of reading an

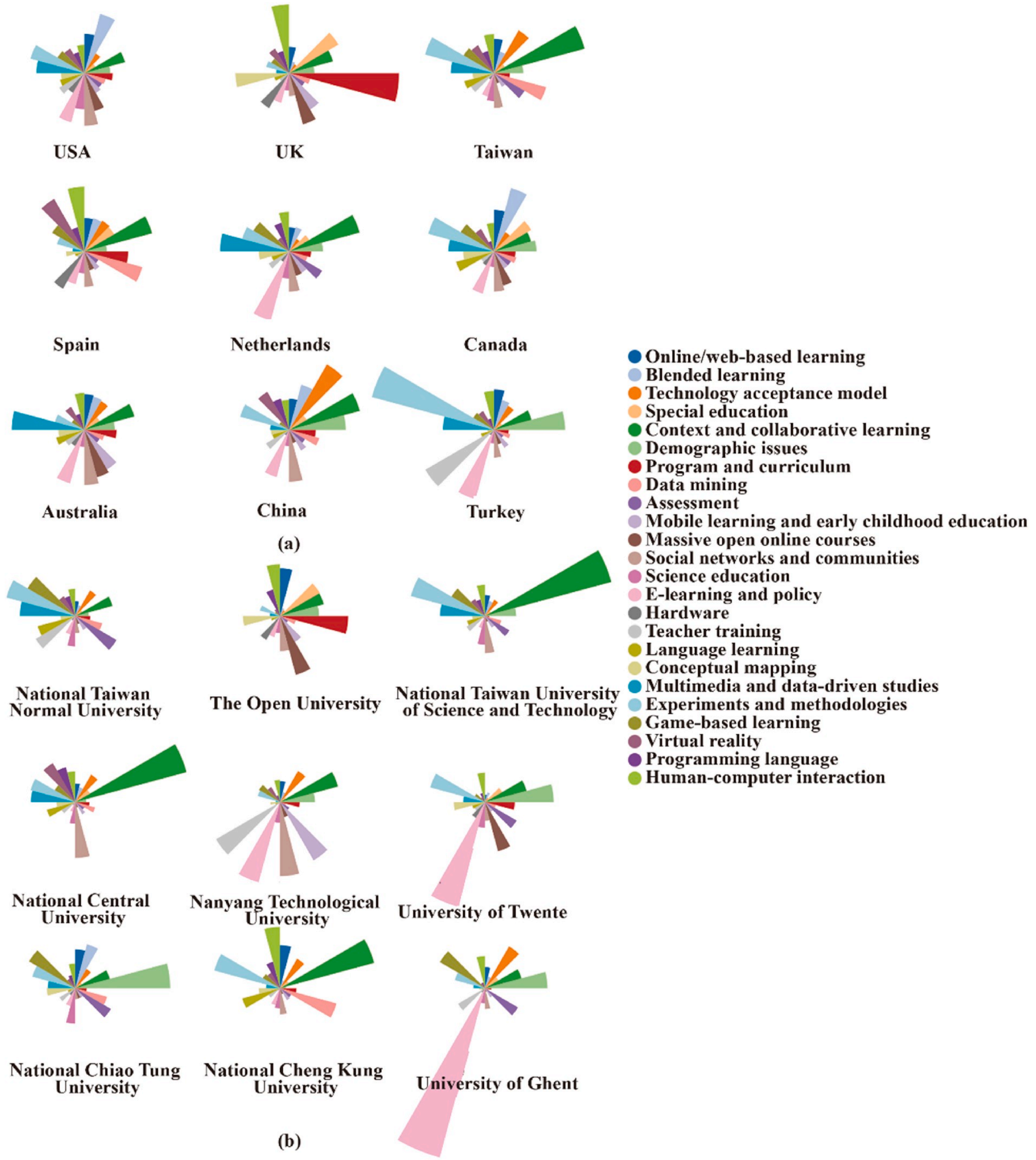

Fig. 8. Topic proportion distributions of the prolific countries/regions and institutions in the publications of *Computers & Education*.

illustrated science text. For *Technology acceptance model,* Sun, Tsai, Finger, Chen, and Yeh (2008) examined the factors influencing learners' satisfaction with e-learning. For *MOOCs*, through evaluating instructional design quality of 76 MOOC courses, Margaryan, Bianco, and Littlejohn (2015) concluded that most MOOCs obtained low scores on their instructional design principles and high scores in their organization and presentation of course materials. For *Conceptual mapping*, through evaluation of the effectiveness of concept mapping for students learning with a hypertext system, Reader and Hammond (1994) concluded thatconcept-mapping improved post-test scores as compared to traditional note-taking,. For *Virtual reality*, Chittaro and Ranon (2007) presented discussions on the use of virtual reality for educational purposes, as well as its possible positive and negative effects, and suggested further potential research directions. For *Programming language,* Chao (2016) studied learners' practices, designs, and problem-solving capabilities concerning

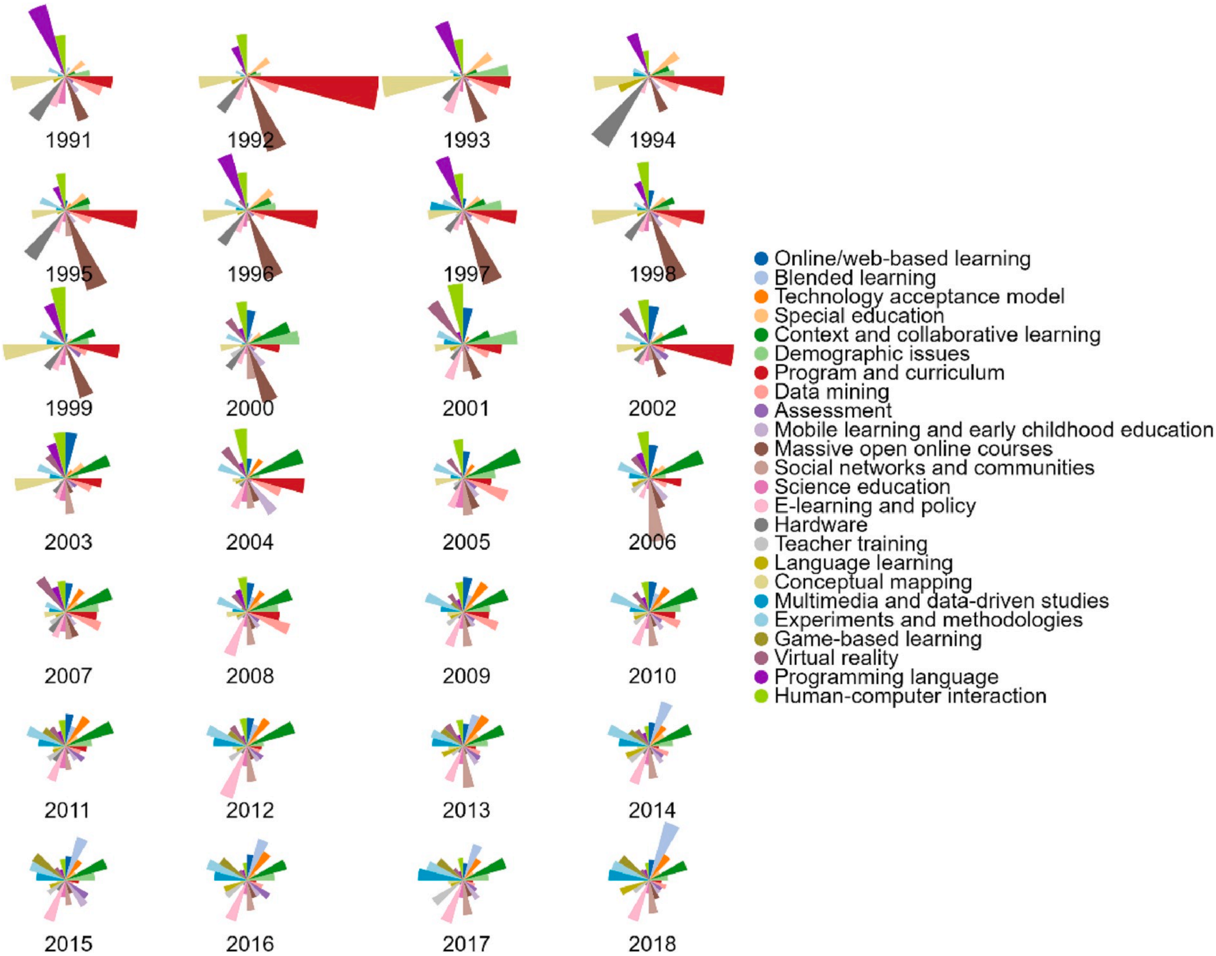

Fig. 9. Topic proportion distributions by year in the Computers & Education publications.

computation in the contexts of visual programming. For *Mobile learning and early childhood education*, Patten, Sánchez, and Tangney (2006) highlighted that the adoption of handheld devices could promote learning. For *Game-based learning,* Huang, Huang, and Tschopp (2010) highlighted the requirements of both motivation-based processing and outcome-based processing during the creation of game-based learning activities. For *Science education*, through evaluation of the unique affordances of augmented reality (AR) in environmental science education, Kamarainen et al. (2013) concluded that a combination of AR and probes had the potential to enhance learning. For *Teacher training,* Angeli and Valanides (2009) presented several issues regarding technological pedagogical content knowledge (TPACK). For *Language learning*, Korat. (2010) investigated how reading an e-storybook influenced kindergarten children's language and literacy. For *Special education,* Parsons, Leonard, and Mitchell (2006) employed a qualitative case-study approach to illustrate the observations of, as well as comments from, two teenagers with autism. For *Assessment,* through the examination of how different online peer feedback affected high-school students, Tseng and Tsai (2007) highlighted the utility of reinforcing peer feedback, as well as the unsuitability of didactic and corrective feedback for students' development of better projects. For *Hardware,* through a comparison of remote and hands-on laboratories, Nickerson, Corter, Esche, and Chassapis (2007) presented an innovative method for evaluating the effectiveness and utility of engineering laboratories for educational purposes. From these representative research works, readers can obtain an in-depth understanding of major issues concerned by the *Computers & Education* community.

4.2. Interpretations of the most studied topics with significantly increasing trends

Of the topics that exhibited statistically significant increasing trends, four topics registered a proportion exceeding 5%, namely *Context and collaborative learning, E-learning and policy, Experiments and methodologies*, and *Social networks and communities*. These topics were the most prominent and significant issues that were discussed among the *Computers & Education* authors.

First, the topic *Context and collaborative learning* accounted for the largest proportion (7.49%). The discriminating terms such as "collaborative", "cooperative", "collaboration", "CSCL", and "context-aware" demonstrated the popularity of collaborative learning and context learning in *Computers & Education* research. CSCL tools had been widely used to assist students to employ collaborative learning to improve learning outcomes (Splichal et al., 2018). Fu, Wu, and Ho (2009) investigated how a productive learning atmosphere was developed in a web-enhanced learning context and concluded that strategies of cooperation within the group and competitions between groups were ideal, because competitions and cooperation promoted development of various types of knowledge.

Second, *E-learning and policy* comprised a proportion of 6.61%, with the most discriminating term being "ICT." ICT interactive applications like blog and blackboard had contributed greatly to the success of e-learning systems (Hernandez, Montaner, Sese, & Urquizu, 2011). Furthermore, scholars as well as policy-makers demonstrated increasingly more awareness of the importance of ICT policy plans for educational purposes (Vanderlinde, van Braak, & Dexter, 2012).

The third topic was *Experiments and methodologies* (6.01%). The relevant studies on this topic were commonly experiment-based or test-related. For example, by using a non-equivalent quasi-experiment with senior high school students taking biology courses, Owusu, Monney, Appiah, and Wilmot (2010) examined the comparative effectiveness of computer-enhanced instruction and traditional instruction. Using an experimental design method with fourth-grade students, Pilli and Aksu (2013) investigated how Frizbi Mathematics 4 affected students' achievement, retention, and attitudes towards math and computer-enhanced instruction methods.

In addition, *Social network and communities* (5.19%) was also an imporatnt topic, with discriminating terms including "community," "computer-mediated communication (CMC)," "synchronous, discussion," "message," "forum," "social," "networking," and "twitter." CMC is "communication between individuals and among groups via networked computers" (Naidu & Järvelä, 2006, p. 1). Social networking sites were widely utilized for educational and professional development purposes (Kimmons & Veletsianos, 2014). Xie, Miller, and Allison (2013) conducted an investigation to understand situations in which social conflicts were introduced into peer-moderated discussions in online courses. Wise and Cui (2018) compared social relations and the underlying interactions relevant and irrelevant to the learning of a MOOC about statistics.

4.3. Global changes of research topics/trends

In addition to the aforementioned topics, several other topics demonstrated global changes of research trends. On the one hand, some topics showed fluctuations in their shares of the corpus, with some emerging to become highly discussed, indicating the shifting tendencies in the research interests of the *Computers & Education* authors. For example, topics such as *Blended learning*, *Technology acceptance models*, and *Game-based learning* had started to gain increasing attention from the academia since the period 2003-2006, demonstrating a growing enthusiasm among scholars in teaching and learning using technologies and games. For example, Chen et al. (2018) explored productive learning performances of learners, with the help of instant revision feedback in the context of blended learning. Shih, Liang, and Tsai (2019) investigated college students' self-regulation in flipped classrooms, using the structural equation modeling method. Prasad, Maag, Redestowicz, and Hoe (2018) investigated post-graduate information technology students' behavioral intentions towards using a blended learning program. Homer, Plass, Raffaele, Ober, and Ali (2018) focused on improvements of the executive functions of high-school students by means of digital games. It is thus reasonable to predict that the use of technologies and games for educational purposes will continue to represent a promising research area. *Teacher training* also showed a continually increasing research trend since the beginning of the studied period. As pointed out by Yeh, Hsu, Wu, and Chien (2017), with TPACK, teachers were able to select suitable instruction technology and adopt it for educational purposes. The integration of TPACK into teaching practices related to "the knowledge constructs that teachers in the digital era develop for and from their teaching practices with technology" (Jen, Yeh, Hsu, Wu, & Chen, 2016, p. 1). Such topics are still of research potential and tend to continue to be the research foci in future.

On the other hand, research interest in topics such as *Special education*, *Language learning*, *Mobile learning and early childhood education*, *Social networks and communities*, and *Science education* seemed to have been stable since about 2006. As indicated by Martin et al. (2011, p.10), who in 2010 reported that "social web and mobile devices are currently the most important technologies for the near future in education," the integration of social networks and mobile devices in education had played a continuingly important role, however, without a corresponding increasing research trend. In this sense, we may conclude that such research seems to be sufficiently mature in education and is less possible to attract more attention in the near future. Lin et al. (2019) examined how learners' perceptions of learning practices correlated with relevant self-efficacies concerning mobile-enhanced, seamless science learning. Tsai and Tsai (2019) examined how pre-service instructors' conceptions of teaching with mobile devices correlated to the quality of technology incorporation into their lesson plans. Additionally, research enthusiasm in topics such as *Virtual reality*, *Context and collaborative learning*, *MOOCs*, and *Human–computer interaction* in the contexts of education seemed to have been declining since about 2000–2003. In particular, topics such as *Program and curriculum*, *Hardware*, *Conceptual mapping*, and *Programming language* had received a continually decreasing research interest since earlier years. Drom the above analyses, we conclude that these topics are very likely to be less popular in the near future.

4.4. Topic correlations

From the topic correlation graph in Fig. 7, some implications can be drawn. For example, several topics, including *Social networks and communities*, *Online/web-based learning*, *Blended learning*, and *Technology acceptance model*, at the lower left-hand side seemed to be closely correlated. These four topics all involved the integration of innovative technologies, such as social networks and the Web in learning and teaching. In blended learning, classroom courses could be supported by different types of materials provided in various technological formats (Van Niekerk & Webb, 2016). According to Chau (1996, p.1), the "technology acceptance model is one of the most influential research models in studies of the determinants of information systems/information technologies," especially for online/web-based learning.

The three topics *MOOCs*, *Hardware*, and *Program and curriculum*, were closely related. MOOCs had attracted learners from various educational and professional contexts. *Hardware* concerned curriculum-related issues particular within web-based contexts, for example, public key infrastructures (Chadwick, Tassabehji, & Young, 2000) and computer-aided design programs (Johnson & Diwakaran, 2011).

In addition, several topics in the upper right-hand side were closely linked. Among them, three topics, namely *Conceptual mapping*, *Assessment*, and *Special education*, could be considered as specific purposes or issues in teaching and learning. However, another three topics including *Programming language*, *Multimedia and data-driven studies*, and *Data-mining* could be regarded as analysis methods or techniques. Their links indicated the widespread use of analysis methods for the solution of complex issues. For instance, Akçapınar (2015) explored how feedback, produced automatically using text mining techniques, affected plagiarism in online coursework.

4.5. *Scientific collaboration and topic distributions of the main contributors*

The topic distributions of the main contributors showed which countries/regions and institutions were more active in the *Computers & Education* community as a whole, or within a particular aspect. Compared with the institutional perspective, the topic distributions of countries/regions seemed to be more balanced, especially for the USA and Canada. However, the topic diversities amongst institutions were more important.

Further combining the scientific research collaboration analysis results, it seemed that the topic distribution patterns of some prolific countries/regions with close collaboration tended to be similar (e.g.,Australia and the Netherlands, as well as the USA and Canada). However, the results were not very significant for the countries/regions with the closest collaboration, for example, the USA, Taiwan, and China. The closely collaborative institutions tended to show similar topic distribution patterns, especially those from the same countries/regions. Take the five institutions from Taiwan as an example. Almost all five were more active in the research on *Context and collaborative learning* as well as *Experiments and methodologies*, compared to the research on other topics.

4.6. *Insights from annual topic distributions*

The results of the annual topic distributions indicated that the trends between some of the topics changed with time, with some topics emerging to become popular amongst the community, indicating shifting tendencies in the publications of *Computers & Education*. For example, in earlier years, authors in the community primarily focused more on topics such as *Programming language*, *Program and curriculum*, *Conceptual mapping*, *Hardware*, and *MOOCs*. As time went by, more topics had received increasing attention within the *Computers & Education* community. For example, *Conceptual mapping* gained greater attention from the community during the period 1991–2003, while *Hardware* was most popularly studied in the period 1991–2000. *Context and collaborative learning* had started to gain more attention since approximately 2000. Among authors, there was a growth of interest in *E-learning and policy* since about 2008. There had been an increasing trend of research into *Social network and communities* since about 2003. *Multimedia and data-driven studies* and *Experiments and methodologies* had received more attention since about 2009. In addition, *Teacher training* had become very popular within the *Computers & Education* community since about 2013.

4.7. *Implications for future directions concerning educational technology*

Based on the findings of the topic modeling analyses, several promising future directions for the educational technology field can be suggested for technological designs and uses in educational settings. For example, game-based learning seems particularly promising. In particular, studies evaluating the effectiveness of learning with games with the use of experimental designs are highly encouraged. As indicated, "game-based intervention is an approach where games such as computer-based narrative games, are used to enhance learning" (Jamshidifarsani, Garbaya, Lim, Blazevic, & Ritchie, 2019, p. 19), and gamification served to enhance learning attendance, motivation, and engagement, all of which were essential for the development of reading skills (Gooch, Vasalou, Benton, & Khaled, 2016; Hong & Masood, 2014). In this sense, research on the gamification of reading interventions is a promising direction for future research (Jamshidifarsani et al., 2019). Blended learning is another research area of great promise. Cloud computing had received attention from scholars who were interested in providing solutions to the issues surrounding tacit knowledge conversion within a blended collaborative learning context (Uden, Liberona, & Welzer, 2014). Studies had been published (for example, Mtebe, 2013; Mtebe & Kissaka, 2015) regarding the significance of utilization of particular cloud computing instruments for the promotion of particular collaborative learning activities. In addition, it is found that collaborative learning was useful in improving learners' achievement and engagement (Quaye & Harper, 2014). However, research on the combination of cloud computational techniques and blended learning for conducting collaborative learning activities remaines limited (Al-Samarraie & Saeed, 2018). Moreover, according to our study, *Blended learning* had received a significantly increased amount of attention, particularly in collaborative learning contexts, and its promising directions relate to social networks and communities, as well as online/web-based learning research.

In addition, correlation-based topical analysis provided insights into potential inter-topic research by identifying topics with strong correlations. For example, one potential research direction is that of multi-disciplinary methods, designed by integrating context and collaborative learning, social networks and communities, blended learning, online/web-based learning, and technology acceptance models in order to develop adaptable and adaptive online and web-learning platforms and applications. In this way, the relationship between approachability and e-learning for scholars, instructional creators, technical personnel, as well as users can be strengthened by offering services to meet an individual's needs (Cinquin, Guitton, & Sauzéon, 2019). In contrast, the multi-disciplinary groups formed by decreasing topics, such as *Human–computer interaction*, *Virtual reality*, *Program and curriculum*, *Hardware*, and *MOOCs*, are possible to be less popular.

5. Conclusion

This study presented an STM topic modeling-based bibliometric analysis to answer questions such as "in what research topics were the *Computers & Education* community interested," "how did such research topics evolve over time," and "what were the main research concerns of the major contributors." The major contributors to the *Computers & Education* research were identified, and the scientific collaborations among them were also visualized. The topic-based bibliometric analysis contributed to *Computers & Education* by providing a comprehensive overview of its community. Moreover, the findings were beneficial to the resource allocation by decision-makers, including the potential contributors to *Computers & Education* and the *Computers & Education* editors who decide the directions and policies of *Computers & Education*. In addition, as *Computers & Education* is "one of the oldest, most established, and prestigious journals in the field of educational technology and computer-assisted learning, with a high impact in terms of citations" (Zawacki-Richter & Latchem, 2018, p. 2), implications of the present study can assist research governors and funding agencies in their research policy-making decisions in relation to educational technology. The exploration of important topics, topic prevalence and developments, and emerging inter-topic directions are helpful for the identification and comparison of current and potential scientific strengths. Research governors or funding agencies can optimize research policies to vigorously promote current and potential competitive research areas and enhance scientific communication and collaborations with promising countries/regions or institutions in specific research areas in order to bolster scientific activities.

As it explores the structures and research topics within the *Computers & Education* corpus, this review study serves as a starting point for further in-depth research into technology uses in education. First, since the current findings are based only on a single journal, further investigations with comparable journals are advised to be conducted to investigate the research field of educational technology more thoroughly. Second, as STM allows the incorporation of metadata into the model to evaluate how metadata affect topic prevalence, further explorations of topic prevalence in different varieties, such as international collaboration and funding information, are recommended. In addition, the discussed research scope of educational technology is relatively broad, thus a detailed level of categories, for example, learning domains such as medicine and science, as well as technological domains such as mobiles, could be considered in future research to provide insights within a particular domain.

CRediT authorship contribution statement

Xieling Chen: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Di Zou:** Conceptualization, Methodology, Validation, Formal analysis, Writing - review & editing, Visualization. **Gary Cheng:** Visualization, Supervision, Project administration, Funding acquisition. **Haoran Xie:** Conceptualization, Methodology, Formal analysis, Data curation, Writing - review & editing, Supervision, Project administration, Funding acquisition.

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Appendix A. Supplementary data

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