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How Do People Do It?

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Abstract. Conceptual modelling involves many higher order cognitive processes, such as relational reasoning and abstraction, which are based on integration and maintenance of information. Evidence from cognitive psychology suggests that these processes are subject to individual differences which cannot be explained by training and experience alone. In this review, we study how the cognitive processes that enable modelling interact to produce modelling behaviour, and where in this process we can find individual differences that may explain some of the variation in performance seen in actual modelling settings. We discuss interaction between working memory, executive control and attention as they facilitate relational reasoning and abstraction, which we consider to be key cognitive processes in modelling. Eventually, a thorough understanding of modelling cognition can help us to provide better cognitive support for modellers.

Keywords: Abstract reasoning, Collaborative modelling, Executive control, Working memory, Attention

1 Introduction

Conceptual modelling is a core activity in system analysis [27], [53], involving reasoning with concepts and the relations between them. Good models rely on principles like modularity, abstraction and hiding [56]. Relevant information to the part of the system under study has to be related, and irrelevant information be made inaccessible so that it cannot exercise unwanted influences. However, there are great differences between modellers in their approach to forming abstractions. Thus, the quality of the resulting abstractions varies [67], sometimes to the detriment of the modelling session. In fact, "practitioners report that conceptual modelling is difficult and that it often falls into disuse within their organisations" [66]. Yet, modelling provides a framework for communication between developers and users, helps analysts understand a domain, provides input for the design process, and documents original requirements for future reference [66].

Hence, we need a more thorough understanding of abstraction in modelling so that targeted interventions for weak modellers may be provided. For this, we must identify which cognitive variables are involved and how they interact. In this article, we provide a high-level overview of these variables, which serves as a starting point for further, more fundamental study. We propose that relational reasoning and abstraction are key cognitive processes in modelling. They depend on the selection, maintenance and integration of relevant information, with constant monitoring for consistency and integrity. All these processes make use of executive control and goal pursuit, which in turn depends on working memory capacity [6], which is influenced by attention span [38] and emotional markers [8].

We begin with a brief review of relevant modelling concepts, then we continue with a discussion of what abstraction is and how it influences relational reasoning in modelling. Then, we relate this to the concept of executive control and its facilitators. Finally, we discuss sources of individual differences and possible implications for training modellers.

2 A Conceptual Analysis of Modelling

First of all, for clarification, we will briefly review modelling concepts. A *model* is an abstract unambiguous representation of a domain of interest, comprising concepts and relations [52], [22], which illustrates the behaviour and structure of a real-world system. In an ideal situation, the model should reflect the goals of the modellers and the stakeholders, and their knowledge and experience of the domain. Individuals involved in the modelling session are either modellers or model viewers. The *modeller* creates the model, first conceiving a mental model of the domain by reasoning from his prior experience and with the input he obtains from the environment [52], [27], [36]. His conception must then be written down as accurately as possible using a certain modelling language [27]. The *model viewer* is concerned with reading and understanding the model. He constructs an internal representation of the domain based on the information contained in the model, the specifics of the modelling language's grammar and symbols and his own previous experience [27]. Afterwards, his feedback provides input for the next iteration. Thus, *modelling* is the process of purposely creating a model based on the modeller's conceptions of the domain [52].

Modelling can be seen as a type of ill-structured problem solving. The initial state, the permissible operators, the optimal solution path and the goal state are not clearly defined or described [14]. For example, imagine designing a system which has to handle incoming data about how often employees have taken sick leave, in order to calculate their pension. Data has to be correct, complete and on time, so certain checks should be in place. In addition, all sorts of exceptions to the rule have to be built into the system. Decisions have to be made on how to represent the flow of information, about which activities can be scoped within one flow and which ones form different flows. Such an ill-structured problem requires a cyclic approach. Information must be interpreted and structured. Abstraction helps the modeller to distinguish which properties are shared by certain activities, as well as to scope the information and to integrate various perspectives. At this point, the modeller can start thinking about a solution strategy, monitoring and evaluating each solution step as he proceeds [51]. Unfortunately, there is a large gap between what modellers *know* about a domain and how they make explicit their *represention* of it to others [28]. Moreover, the reasoning process is influenced by the amount of domain knowledge and the extent to which the forming of relations is required [36].

The discrepancy between the information known and information represented can be more explicitly described, respectively, in terms of the distinction between reading and writing a model [27]. Reading and writing are significantly different processes which will nevertheless alternate frequently within a modeller as he pauses to reflect, or listens to feedback. In the case of writing, the way the modeller understands the domain may not be accurately reflected in his model, while, in the case of reading, the understanding of the domain that the model viewer has constructed from the model may not match what the model is intended to represent. Active reasoning about the domain, if done by both modellers and model viewers, may eliminate these discrepancies [27]. Comprehension based on active reasoning leads to a deeper understanding of the domain, which is not the case with the passive comprehension based on recall. Active reasoning demands that viewers use the information represented to construct an answer to a problem related to the domain, an answer which cannot be immediately deduced from the model. This is true regardless of the modelling technique used [27].

The influence of domain knowledge on the reasoning process depends on the complexity of the relations involved. An expert in a domain should have his knowledge about it efficiently organised in his mind and know how to use the information. This would allow him to see meaningful patterns easily, and thus realise their strategic implications. However, solely domain knowledge is not always sufficient for solving a reasoning problem [39]. For this, *integration* of relations is required. Maier [39] shows that only once something "related to integration" was cued, solutions began to emerge. When relational integration fails, "inadequate responses based on native and acquired mechanisms are applied" [39]. This has been illustrated in a study on the effect of domain knowledge in modelling tasks. In tasks that require little relational integration, such as those in which extracted knowledge is directly represented in the model, domain knowledge has no effect on modelling performance. However, domain knowledge greatly improves performance on tasks which do require relational integration [36].

3 The Cognitive Mechanism of Modelling

In order to understand why difficulties in modelling occur so widely, we have to take the mechanism of modelling into account. As previously mentioned, comprehension is achieved through relational reasoning, making use of both experience and new knowledge. Abstraction leads to a model conveying only the essential information relevant to a certain goal. It determines the way concepts are represented in the model. Also, by reaching a higher abstract understanding of a relation, reasoners are able to make inferences beyond the direct consequences [40]. Abstracting to the right level is strongly subject to individual differences, both in terms of experience and capacity, which will be discussed later. We will first discuss the forms and core properties of abstraction to help us understand how abstraction shapes relations. Then, we elaborate on relational reasoning in modelling.

3.1 Concepts and Relations

The main forms of abstraction we encounter during modelling are *concepts* and *relations*. Generally speaking, concepts are "what enables us to interpret situations in terms of previous situations that we judge as similar to the present" [25]. They participate in the generation of meaning based on a vast body of concrete knowledge. Without the information contained in a concrete situation, the concept would not be able to acquire any meaning [54]. Thus, the context dynamically influences the interpretation and structure of a concept [25]. For example, *fast* can only be truly appreciated when considered in relation to a set of observations of different speeds.

Formally, a relation is a "binding between a relation symbol and a set of ordered tuples of elements" [30], such as *faster*(hare, tortoise). A relation describes the behaviour between two or more concepts. Relations are needed for constructing a process, in which they may acquire different complexities. Relational complexity is determined by the "number of related dimensions that need to be considered jointly to arrive at the correct solution" [19]. As is the case with concepts, a relation also does not become meaningful without a thorough, concrete understanding of the concepts it binds. Hence, concepts and relations depend on each other to acquire meaning. In a model, relations determine the position of different concepts. Relational knowledge has three essential properties which must be satisfied at all times during the reasoning process [30]. Representations have to maintain form across different levels of abstraction (*structure consistency*), and retain their meaning when participating in compound representations (*compositionality*). Also, if one can understand the meaning of a relation, then one can generate novel instances for that specific relation (*systematicity*). These properties ensure that relations retain their integrity, both internally and in the context of the whole model.

3.2 Properties of Abstraction

To begin with, an abstraction represents the innermost essence of a concept in a given context [3]. In an early theory of abstraction, George Berkeley (1685 - 1753) proposed that abstraction occurred through a "shift in attention"; one can focus on a particular feature of a single object, and let that feature represent a whole group of objects [9]. Rosch et al. [55] have identified a highly inclusive level of abstraction that most people perceive as 'basic', for which Berkeley's view might apply. Instances at this level possess a great number of common attributes and have similar motor programs. As a consequence, potential category members may be identified by averaging the shapes of other members. However, a nuance to this view is necessary, as abstractions only become meaningful through coherent relations between features. Single distinctive attributes or random collections of properties turn out to be highly inadequate [3], [37].

A second property of abstraction is that it allows us to reason with generalities rather than instances. When observing a set of concrete instances, one can infer similar properties and use this knowledge in combination with experience to classify novel objects. As this process advances, concrete objects are replaced by simple propositions [21]. Abstract thought can then be used to perform mental operations on such object representations and possible actions in the mind [48]. It should be noted, though, that abstraction and generality are not synonymous. Rather, generality is required for abstraction, but abstraction is also required for generalisation [3]. This cyclic statement poses a problem: it implies that a certain abstract concept has to be present before any abstraction can be made. We can solve this by viewing concrete concepts as the aforementioned simple abstract representations [21] without breaking any rules of abstraction, for any mental representation is an abstraction and not the real object.

Thirdly, abstractions can form the basis for the creation of more complete descriptions [3]. This is illustrated in a study of how linguistic ideas are abstracted [11]. Upon hearing and later recalling semantically related sentences, the abstracted representations ended up being far more complete than the original sentences ever were, because relations were supplemented with available knowledge. Hence, we see how the link to an individual's experience is made through active memory (re)construction and how experience influences abstract ideas.

A fourth feature is the relativity of abstraction. Barsalou [7] writes that abstractions are dynamic, tailored to a purpose, temporary, flexible, become more easy to use with practice, and involve attention shifting. Formation of abstractions are influenced by available knowledge structures, intentions, goals, experience, and the beholder's context. Therefore, people differ in what they consider abstract or concrete, and this may change as experience develops and contexts change. In practice, people reason on a certain 'preferred level of abstraction' [26], which appears to be mostly context-dependent, fluctuates widely over time and is independent of the capacity to abstract and of general intelligence. In some cases, the automaticity of previous experiences and habits primes future abstractions regardless of the context, even in the presence of accessible abstract rules.

Finally, abstractions are complex, and the required mental effort to form abstractions increases proportionally with the level of abstraction, which is independent of task difficulty [15]. The balance between the level of detail and the generic structure in a model is a delicate one. If we move down a level towards describing concrete instances, knowledge becomes much more specialised. Details become voluminous and minutely distinguishable as they may be semantically or visually related. Considering them all would lead to an attention overload. On the other hand, if detailed information is lacking, grasping the meaning of an abstraction becomes impossible. Before being able to see high-level structures and generalities which can be used in productive thinking, a whole range of behaviours a concept may exhibit has to be well understood [3].

3.3 Relational Reasoning in Modelling

Relational reasoning is "the ability to consider relationships between multiple mental representations" [19], and is implied in tasks requiring conceptual relations [12]. The purpose of reasoning is to form conclusions, judgments, or inferences from facts or premises. The resulting relations eventually make up the model. Reasoning combines separate past experiences and novel input in such a manner as to achieve a goal, or to meet the demands of a situation. In this context, it is important to distinguish between two types of information processing that may take place during reasoning: analytic and nonanalytic cognition [33]. Analytic cognition involves breaking a stimulus into relevant and irrelevant features, and generality stems from a certain configuration of recombinable units. In contrast, nonanalytic cognition relies on referring back to specific prior episodes, thereby incorporating real-world knowledge, and generality results from finding analogies between similar situations [33]. Both involve abstracting relevant features, and maintaining and comparing them in mind. In the latter case, though, recombination has already taken place.

Abstraction in relational reasoning manifests as flexible switching between concrete and abstract representations, and shifts in focus on certain relevant properties. These could be considered meta-relations across knowledge. Bearing the properties of relational knowledge in mind (structure consistency, systematicity and compositionality [30]), we can distinguish two types of switching strategies. The first type of switching could be considered 'vertical': shifting up and down between abstraction levels through generalisation and instantiation [61]. This is how the model is made *meaningful* by actively connecting generic concepts to what the evolving model means in terms of the activities and objects a modeller or user encounters in his daily environment. Sometimes the connection between concrete and abstract goes awry. Usually, people know only partly how the complex systems they work with function, rendering it very hard to make explicit procedural or tacit knowledge [43]. Such concrete knowledge gaps can result in faulty conceptions of a domain, a failure to monitor understanding and progress, and thereby hamper success at problem solving. It has been observed, though, that if concepts turn out to be too abstract to understand, unconscious reduction of the abstraction level takes place [31]. The second type of switching is 'horizontal', in the sense that even though attention shifts to a different focus or context, the same concept is still being considered. If the context shifts, so do the features that have to be considered and they may acquire totally new meanings [39]. In such cases structure consistency and compositionality must be monitored to maintain model integrity. Thus, relations can be made between concepts based on those properties relevant for the situation, otherwise they may be ignored [56], [61]. However, omitted information is only made inaccessible so that it does not affect the part of the system under consideration. This is known as *hiding* [56].

4 Reasoning Explained in Cognitive Processes

In order to avoid violating any of the properties of relational knowledge during reasoning so that meaningful relations may be formed, through analytic and non-analytic cognition, involvement of executive control functions is required [16], [19]. Essentially, executive functions control and coordinate behaviour so that people can achieve goals in an efficient manner. It allows people to inhibit distractions and irrelevant routine behaviours, and monitor their progress through controlled attention, regardless of the specifics of the task [29]. Also, it facilitates critical reflection, which is essential to consolidating knowledge and learning [65]. When central executive functioning is disrupted, performance on conditional reasoning tasks suffers considerably [63]. In an extensive review, Alvarez & Emory [2] find that the processes underlying executive functions are inhibition and switching, working memory and selective and sustained attention. We will discuss modelling in terms of each of the underlying processes.

4.1 Executive Control and Goal Pursuit: Facilitators of Reasoning

During modelling, a modeller may participate in diverse cognitive activities, such as to select the relevant information, and to regulate and monitor his selection in case of multiple simultaneous inputs. He must read, interpret and comprehend this information, and match his own mental representation with what other modellers are saying and writing. Moreover, modellers should not only monitor themselves, but also monitor others in the flow of discussion so that they can react appropriately to other participants, providing them with information to interpret [67]. At the end of the session, the modeller needs to relate the modelling goals and the users' needs to the model created to ensure final model quality [57]. Executive control is thus not only used to monitor the information being processed, but also to interact closely with goal pursuit processes to provide the modeller with a direction in which to operate. Through response inhibition and performance monitoring, the modeller modulates how he responds to a stimulus depending on his goal and context, allowing him to adapt to or to produce consistent output in a novel situation [10]. Goal-seeking behaviour depends very strongly on goal maintenance. Goal-directed selection of information is essential in order to deal with the structure imposed by the reasoning task [16]. It enables searching through memory and selecting relevant information to substitute into the task structure. Also, goals associated with affective markers determine the amount of effort invested in achieving the goal in question [8], and the likelihood of engaging executive control [24]. When positive affect becomes associated or coactivated with a goal concept, motivation and readiness to achieve that particular goal is facilitated, while negative affect is assumed to put preexisting goals on hold [1]. Using affective signals, qualitatively different alternatives can be non-consciously evaluated.

4.2 Working Memory: The Driving Force

Facilitation of executive control depends on the working memory (WM) system; in fact, it is part of the WM system, conceptualised as the 'central executive' component in the model of WM by Baddeley et al. [5]. WM is a limited capacity memory system that deals with both the storage and manipulation of information. Information in WM, whether newly perceived or retrieved from long-term memory (LTM) is ephemeral by nature, but can be maintained by repetition. Evidence suggests that WM is involved in many complex cognitive processes relevant to modelling, such as (relational) reasoning [19], comprehension [38], abstract thought [15], unconscious goal pursuit [23] and problem solving [38]. Across these domains, the essential functional role of WM is primarily concerned with activation, selection, maintenance and manipulation of information to make it relevant for goal and context [44], [46]. WM is suggested to be the 'workspace' where relations are constructed and altered [30]. The WM system maintains representations on a certain level of abstraction [15].

In the Baddeley model [5], storage is composed of an episodic buffer, aided by a phonological loop for processing auditory and speech-based information, and a visuospatial sketchpad for visual images in the context in which we perceive them in the everyday world. Control and manipulation of information happens through the central executive. A slightly different focus is taken by Cowan [17]. He proposed the *Embedded Process Theory*, a hierarchically organised theory in which working memory is based on activated information which is "unusually accessible". Within the LTM store, there is a subset of activated information. This is the short-term store. Within this short-term store there is yet another subset, which is within the focus of attention. The focus of attention determines what information is available to WM, thereby exercising control over WM, while attention span capacity determines how much information can be activated at any given time. Information within the focus of attention is typically used for tasks requiring strong executive control, whereas information within the short-term store can be used for automated, familiar tasks. Despite subtle differences in conceptualisation, the essence of the WM models is that WM is a control mechanism operating on information, residing in LTM stores, made easily accessible.

There is evidence to suggest that for the most part, WM is a fundamental, domain general processing capacity involved in both elementary and complex cognitive processing [38]. However, there does appear to be a certain degree of WM specialisation for specific types of information on a deeper level. Ample evidence points out a differentiation between spatial and non-spatial WM [20], [46]. Spatial WM resources are strongly linked to performance on abstraction and executive control tasks [47]. Concrete reasoning, in contrast, appeared to draw much more on non-spatial, visual WM resources [34]. A constraint on the system is the severely limited number of items that can be held in WM for immediate use. Chen & Cowan [13] show that WM is generally constrained to 3-5 chunks of meaningful items of information, if rehearsal is actively prevented. There is no question that active interference of competing items of information plays a major role in the quick decay of WM content, but the extent to which time-based decay of activated information traces plays a role is not clear. However, in a realistic situation like modelling, it seems unlikely that there is time for temporal decay due to the high volume of interaction and discourse taking place. Thus, we are most likely dealing with interference most of the time. This only emphasises the importance of maintaining a focus during modelling.

4.3 Attention: The Capacity Mediator

Attention allows one to concentrate on a certain set of objects or tasks, in favour of others, thereby assigning a bias to internal representations which serves subsequent cognitive processing. It translates goals into behaviour by orienting an individual towards goal-relevant information, using the affective signals mentioned before to determine relevance [8]. Attention also supervises this process through executive control. Information entering the limited capacity of WM (WMC) is mitigated by attention [38] and time [41]. Both are critical resources to allow invocation of executive processes so that controlled processing can take place. If time is too short for executive processes to be activated, attentional resources cannot be allocated to invoke strategy use. As a consequence, performance on reasoning tasks relies more strongly on basic WM span [41]. Attentional resources are likely shared between different aspects of WM, as illustrated by Just et al. [35], who show that two WM tasks, which draw on different neural systems, show impaired performance when performed simultaneously. WM appears to recruit attention in the service of memory rehearsal [4]. In support of this, it is found that loading WM decreases control of attention over inhibitory and switching functions [32]. Hence, WMC relates directly to attentional control over executive functions. Furthermore, the relation between attention and WMC is influenced by the need for coordination of multiple knowledge representations, when people are required to attend to multiple representations simultaneously to determine which one to use [58]. If no coordination is required, WMC only determines how well stimulus-response associations are learned. If coordination is required, then WMC not only predicts learning performance but also how well people can shift between response strategies.

4.4 Sources of Individual Differences

Both WMC [42], [16] and attention span [26], [38] have proven to be significant sources of individual differences in abstraction, reasoning and problem solving. Even though the WM capacity limit is fixed within the 3-5 range, there are significant individual differences to be observed. Explanations for this are sought in storage and processing capacity variations. There is a debate as to whether the efficiency of processing ability is solely responsible for all WM functionality [42], or whether storage and processing capacities are independent and both contribute to overall individual differences [18]. In favour of the first perspective, individuals with a high WMC were found to be much better at attending to relevant information and thus inhibiting irrelevant information. Low capacity individuals, in contrast, processed both target and distracter information, ending up with far less meaningful information overall and so rendering distractions detrimental to performance [16], [42]. This effect has been demonstrated for the auditory [39] and the visual modality [64]. On the other hand, in favour of physical storage capacity, Todd & Marois [62] show that in the absence of processing requirements, brain activity in the posterior parietal areas correlated with WM performance.

5 General Discussion

In modelling literature, many authors have made reference to either executive control or working memory in attempts to understand and support modelling. For instance, Sutcliffe & Maiden [60] implicitly identify differences in executive control processes in weak and strong novices. Pinggera et al. [49] relate the use of structure during modelling to higher quality models. Finally, Moody [45] emphasizes the role of WM in understandability of models. However, the psychological frameworks used do not describe modelling behaviour in terms of its facilitating variables. Furthermore, when designing protocols for modelling support, this only led weak modellers to rigidly follow the protocol and it did not impart understanding of the modelling problem [60]. Similarly, even though both WM capacity and attention span have been subject to training, it is unclear whether WMC can actually be increased. While WM training appears to improve task performance, Shipstead et al. [59] point out that it has not yet been shown that this effect is directly due to an increase in actual WM capacity. Since the mechanisms of WM transfer to other skill domains are unclear, the observed improvement might well be due to a learning effect. Also, transfer to improved attention could not be attributed to WM. Therefore, we need to study modelling beyond the behavioural level, going as far as to study its neural substrates. The neural workings can eventually be used as a model for targeted intervention.

To a certain extent, the strategy of creating awareness has yielded some results. Increasing attention to relevant features improves performance in abstract tasks [50]. Awareness of attending to features increased analytic processing. Explanation of this effect in terms of mental model theory [34] would state that mental models are being further elaborated by paying attention to those features that were still missing.

In conclusion, we argue for a cognitive system enabling modelling in which executive control monitors information processing for integrity of representations. Switching between abstraction levels and different contexts, and inhibiting distracting information are primary processes. Also, it interacts with goal pursuit to maintain relevant goals, making use of affective body signals. Executive control is part of WM, which facilitates storage of representations and processing of content information. WM has a limited capacity, which is subject to individual differences. A source of differences is the ability to mediate attention between relevant and irrelevant stimuli competing for processing.

References

1. Aarts, H., Custers, R., Holland, R.W.: The nonconscious cessation of goal pursuit: When goals and negative affect are coactivated. Journal of Personality and Social Psychology 92(2), 165–178 (2007)
2. Alvarez, J.A., Emory, E.: Executive function and the frontal lobes: A meta-analytic review. Neuropsychology Review 16(1), 17–42 (2006)
3. Arnheim, R.: Visual Thinking. University of California Press (1969)
4. Awh, E., Jonides, J.: Overlapping mechanisms of attention and spatial working memory. Trends in Cognitive Sciences 5(3), 119 – 126 (2001)
5. Baddeley, A., Logie, R., Bressi, S., Sala, S.D., Spinnler, H.: Dementia and working memory. The Quarterly Journal of Experimental Psychology Section A 38(4), 603–618 (1986)
6. Bailey, H., Dunlosky, J., Kane, M.: Why does working memory span predict complex cognition? testing the strategy affordance hypothesis. Memory & Cognition 36, 1383–1390 (2008), 10.3758/MC.36.8.1383
7. Barsalou, L.W.: Abstraction in perceptual symbol systems. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences 358(1435), 1177–1187 (2003)
8. Bechara, A., Damasio, H., Damasio, A.R.: Emotion, decision making and the orbitofrontal cortex. Cerebral Cortex 10(3), 295–307 (2000)
9. Berkeley, G., Krauth, C.P.: A Treatise Concerning the Principles of Human Knowledge. JB Lippincott & Co. (1878)
10. Berkman, E.T., Falk, E.B., Lieberman, M.D.: Interactive effects of three core goal pursuit processes on brain control systems: Goal maintenance, performance monitoring, and response inhibition. PLoS ONE 7(6), e40334 (06 2012)
11. Bransford, J.D., Franks, J.J.: The abstraction of linguistic ideas. Cognitive Psychology 2(4), 331 – 350 (1971)
12. Cattell, R. (ed.): Intelligence: Its Structure, Growth and Action, Advances in Psychology, vol. 35. North Holland (1987)
13. Chen, Z., Cowan, N.: Core verbal working-memory capacity: The limit in words retained without covert articulation. The Quarterly Journal of Experimental Psychology 62(7), 1420–1429 (2009)
14. Chi, M.T.H., Glaser, R.: Problem solving ability. In: Sternberg, R.J. (ed.) Human Abilities: An Information Processing Approach, chap. 10. Freeman New York (1985)

15. Christoff, K., Keramatian, K., Gordon, A., Smith, R., Mädler, B.: Prefrontal organization of cognitive control according to levels of abstraction. Brain Research 1286, 94–105 (2009)
16. Chuderska, A.: Executive control in analogical mapping: Two facets. In: Proceedings of the 32nd Annual Conference of the Cognitive Science Society. pp. 2749–2754 (2010)
17. Cowan, N.: An embedded-processes model of working memory. In: Miyake, A., Shah, P. (eds.) Models of working memory: Mechanisms of active maintenance and executive control, chap. 3, pp. 62–101. Cambridge University Press (1999)
18. Cowan, N., Saults, J.S., Morey, C.C.: Development of working memory for verbal-spatial associations. Journal of Memory and Language 55(2), 274 – 289 (2006)
19. Crone, E.A., Wendelken, C., Van Leijenhorst, L., Honomichl, R.D., Christoff, K., Bunge, S.A.: Neurocognitive development of relational reasoning. Developmental Science 12(1), 55–66 (2009)
20. Daneman, M., Tardif, T.: Working memory and reading skill re-examined. In: Coltheart, M. (ed.) Attention and performance, vol. 12, pp. 491–508. Hillsdale: LEA (1987)
21. Diamond, A.: Bootstrapping conceptual deduction using physical connection: rethinking frontal cortex. Trends in Cognitive Sciences 10(5), 212 – 218 (2006)
22. Dietz, J.: Enterprise Ontology: Theory and Methodology. Springer Verlag (2006)
23. Dijksterhuis, A., Aarts, H.: Goals, attention, and (un)consciousness. Annual Review of Psychology 61, 467–490 (2010)
24. Dixon, M.L., Christoff, K.: The decision to engage cognitive control is driven by expected reward-value: Neural and behavioral evidence. PLoS ONE 7(12), e51637 (12 2012)
25. Gabora, L., Rosch, E., Aerts, D.: Toward an ecological theory of concepts. Ecological Psychology 20(1), 84–116 (2008)
26. Gardner, R.W., Schoen, R.A.: Differentiation and abstraction in concept formation. Psychological Monographs: General and Applied 76(41), 1–21 (01 1962)
27. Gemino, A., Wand, Y.: Evaluating modeling techniques based on models of learning. Communications of the ACM 46(10), 79–84 (2003)
28. Gemino, A., Wand, Y.: A framework for empirical evaluation of conceptual modeling techniques. Requirements Engineering 9(4), 248–260 (2004)
29. Gilbert, S.J., Burgess, P.W., et al.: Executive function. Current Biology 18(3), 110–114 (2008)
30. Halford, G.S., Wilson, W.H., Phillips, S.: Relational knowledge: The foundation of higher cognition. Trends in Cognitive Sciences 14(11), 497 – 505 (2010)
31. Hazzan, O.: Reflections on teaching abstraction and other soft ideas. ACM SIGCSE Bulletin 40(2), 40–43 (2008)
32. Hester, R., Garavan, H.: Working memory and executive function: The influence of content and load on the control of attention. Memory & Cognition 33(2), 221–233 (2005)
33. Jacoby, L.L., Brooks, L.R.: Nonanalytic cognition: Memory, perception, and concept learning. In: Bower, G.H. (ed.) Psychology of Learning and Motivation, vol. 18, pp. 1 – 47. Academic Press (1984)
34. Johnson-Laird, P.N.: Deductive reasoning ability. In: Sternberg, R.J. (ed.) Human Abilities: An Information Processing Approach. W.H. Freeman (1985)
35. Just, M.A., Carpenter, P.A., Keller, T.A., Emery, L., Zajac, H., Thulborn, K.R.: Interdependence of nonoverlapping cortical systems in dual cognitive tasks. NeuroImage 14, 417–426 (2001)

36. Khatri, V., Vessey, I., Ramesh, V., Clay, P., Park, S.: Understanding conceptual schemas: Exploring the role of application and is domain knowledge. Information Systems Research 17(1), 81 (2006)
37. Lakoff, G.: Cognitive models and prototype theory. In: Margolis, E., Laurence, S. (eds.) Concepts: Core Readings, chap. 18, pp. 391 – 421. The MIT Press (1999)
38. Lépine, R., Parrouillet, P., Camos, V.: What makes working memory spans so predictive of high-level cognition? Psychonomic Bulletin & Review 12, 165–170 (2005), 10.3758/BF03196363
39. Maier, N.R.: Reasoning in rats and human beings. Psychological Review 44(5), 365–378 (1937)
40. Manktelow, K., Fairley, N.: Superordinate principles in reasoning with causal and deontic conditionals. Thinking & Reasoning 6(1), 41–65 (2000)
41. McCabe, D.P.: The influence of complex working memory span task administration methods on prediction of higher level cognition and metacognitive control of response times. Memory & Cognition 38(7), 868–882 (2010)
42. McCollough, A., Vogel, E.: Your inner spam filter. Scientific American Mind 19(3), 74–77 (2008)
43. McDermott, R.: Why information technology inspired but cannot deliver knowledge management. California Management Review 41(4), 103–117 (1999)
44. Miyake, A., Friedman, N., Emerson, M., Witzki, A., Howerter, A., Wager, T.: The unity and diversity of executive functions and their contributions to complex frontal lobe tasks: A latent variable analysis. Cognitive Psychology 41(1), 49–100 (2000)
45. Moody, D.L.: The "physics" of notations: Toward a scientific basis for constructing visual notations in software engineering. Software Engineering, IEEE Transactions on 35(6), 756–779 (December 2009)
46. Oberauer, K., Süß, H.M., Schulze, R., Wilhelm, O., Wittmann, W.: Working memory capacity - facets of a cognitive ability construct. Personality and Individual Differences 29(6), 1017 – 1045 (2000)
47. Owen, A.M., Downes, J.J., Sahakian, B.J., Polkey, C.E., Robbins, T.W.: Planning and spatial working memory following frontal lobe lesions in man. Neuropsychologia 28(10), 1021 – 1034 (1990)
48. Piaget, J.: Zes Psychologische Studies. Van Loghum Slaterus (1969)
49. Pinggera, J., Soffer, P., Zugal, S., Weber, B., Weidlich, M., Fahland, D., Reijers, H.A., Mendling, J.: Modeling styles in business process modeling. In: Bider, I., Halpin, T., Krogstie, J., Nurcan, S., Proper, E., Schmidt, R., Soffer, P., Wrycza, S. (eds.) Enterprise, Business-Process and Information Systems Modeling, Lecture Notes in Business Information Processing, vol. 113, pp. 151–166. Springer Berlin Heidelberg (2012)
50. Platt, R.D., Griggs, R.A.: Facilitation in the abstract selection task: The effects of attentional and instructional factors. The Quarterly Journal of Experimental Psychology Section A 46(4), 591–613 (1993)
51. Pretz, J.E., Naples, A.J., Sternberg, R.J.: Recognizing, defining and representing problems. In: Davidson, J.E., Sternberg, R.J. (eds.) The Psychology of Problem Solving. Cambridge University Press (2003)
52. Proper, H.A., Van Bommel, P., Hoppenbrouwers, S.J.B.A., Van der Weide, T.P.: A fundamental view on the act of modeling. In: Kizza, J., Aisbett, J., Vince, A., Wanyama, T. (eds.) Advances in Systems Modeling and ICT Applications, Special topics in Computing and ICT research, vol. 2, pp. 97–112. Fountain Publishers, Kampala, Uganda (2006)

53. Renger, M., Kolfschoten, G., De Vreede, G.: Challenges in collaborative modelling: A literature review and research agenda. International Journal of Simulation and Process Modelling 4(3), 248–263 (2008)
54. Rosch, E.: Reclaiming concepts. Journal of Consciousness Studies 6(11-12), 61–77 (1999)
55. Rosch, E., Mervis, C.B., Gray, W.D., Johnson, D.M., Boyes-Braem, P.: Basic objects in natural categories. Cognitive Psychology 8(3), 382–439 (1976)
56. Ross, D., Goodenough, J., Irvine, C.A.: Software engineering: Process, principles, and goals. Computer 8(5), 17–27 (1975)
57. Sedera, W., Rosemann, M., Gable, G.: Measuring process modelling success. In: Proceedings of ECIS 2002 (2002)
58. Sewell, D., Lewandowsky, S.: Attention and working memory capacity: Insights from blocking, highlighting, and knowledge restructuring. Journal of Experimental Psychology: General 141(3), 444–469 (2012)
59. Shipstead, Z., Redick, T.S., Engle, R.W.: Is working memory training effective? Psychological Bulletin 138(4), 628 – 654 (2012)
60. Sutcliffe, A., Maiden, N.: Analysing the novice analyst: cognitive models in software engineering. International Journal of Man-Machine Studies 36(5), 719 – 740 (1992)
61. Theodorakis, M., Analyti, A., Constantopoulos, P., Spyratos, N.: Contextualization as an abstraction mechanism for conceptual modelling. In: Akoka, J., Bouzeghoub, M., Comyn-Wattiau, I., Métais, E. (eds.) Conceptual Modeling - ER '99, 18th International Conference on Conceptual Modeling, Paris, France, November, 15-18, 1999 Proceedings. Lecture Notes in Computer Science, vol. 1728, pp. 475–489. Springer Berlin / Heidelberg (1999)
62. Todd, J.J., Marois, R.: Posterior parietal cortex activity predicts individual differences in visual short-term memory capacity. Cognitive, Affective, & Behavioral Neuroscience 5, 144–155 (2005)
63. Toms, M., Morris, N., Ward, D.: Working memory and conditional reasoning. The Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology 46(4), 679–699 (2013/02/08 1993)
64. Vogel, E.K., McCollough, A.W., Machizawa, M.G.: Neural measures reveal individual differences in controlling access to working memory. Nature 438(7067), 500–503 (2005)
65. Vygotsky, L.: Mind in Society: The Development of Higher Psychological Processes. Harvard University Press (1978)
66. Wand, Y., Weber, R.: Research commentary: Information systems and conceptual modeling - a research agenda. Information Systems Research 13(4), 363–376 (2002)
67. Wilmont, I., Barendsen, E., Hoppenbrouwers, S.J.B.A., Hengeveld, S.: Abstract reasoning in collaborative modeling. In: HICSS Proceedings. vol. 45 (2012)