Cognitive load in interactive knowledge construction

Abstract

The focus of this special issue is on the cognitive load underlying processes of interactive knowledge construction in a wide range of instructional multimedia platforms. Multimedia comprehension involves the parallel processing of auditory—verbal and visual—pictorial channels within working memory. By means of integrating multimodal information, students are able to acquire new knowledge. However, the processes of knowledge construction may be dependent on the load a task imposes on the learner’s cognitive system. Such cognitive load is determined by prior knowledge, motivation, and processing strategies on the part of the learner as well as on task demands. Other critical factors that should be explored are goal adoption and perspective taking, effects of interactive animation, environmental support, and possibilities of collaboration.

Keywords: Cognitive load; Knowledge construction; Multimedia comprehension

1. Introduction

Over the past decades, the practice of teaching and learning has been evolving from traditional knowledge transmission approaches to constructivist approaches of interactive knowledge construction. This evolution is supported and strengthened by recent findings in cognitive science, which suggest that knowledge acquisition is a constructing process of building coherent mental representations within conceptual frameworks, and that such representations may be built from verbal and pictorial symbols (see Bransford, Brown, & Cocking, 2000). Constructivist theories of learning hold that students use their prior knowledge to construct new knowledge that is relevant to their individual experiences and situations. As regards this perspective, there is a widespread belief that multimedia offer many possibilities to facilitate knowledge construction (cf. Mayer, 2005a, 2005b). Because multimedia become increasingly integrated into the school curriculum, the convergence of instruction in school subjects and web-based information technologies seems inevitable. The requirements of these forms of interactive teaching and learning imply additional cognitive processing, which imposes additional cognitive load on learners’ working memory.

The aim of the present special issue was to develop and validate operational models of the cognitive load that underlies processes of interactive knowledge construction in various instructional settings. We assume that the cognitive architecture of students includes a working memory with limited capacity, which entails subsystems for verbal and pictorial information, and a long-term memory for the storage of prior knowledge. The question is how students acquire new knowledge in multimedia environments with multimodal (visual and auditory) presentation of information when working on multiple tasks and how cognitive overload can be reduced by attuning instructional design to the characteristics of the student.

1.1. Interactive knowledge construction

Constructivist theories of learning assume that students use their prior knowledge to construct new knowledge from the presented information that is relevant for their individual goals and which is based on their individual experiences. There is a widespread belief that knowledge construction is facilitated by technology using multiple channels of communication (see Verhoeven & Graesser, 2008) and that web-based learning demands require accurate instructional design (Van Merriënoor & Kester, 2005). Given the enormous increase of web-based multichanneled technologies, researchers have been exploring how people construct knowledge in interactive environments (cf. Kinzer & Verhoeven, 2008). Interactive knowledge construction is normally facilitated in an environment that stimulates meaningful, social and strategic learning processes (Bransford et al., 2000; Verhoeven, Segers, Bronkhorst, & Boves, 2006). Meaningful learning presupposes that students attend to the essential aspects of the presented material, organize it into a coherent
cognitive structure, and integrate it with what they already know. Social learning occurs when the students learn by observing teachers, tutors, or other students and when they receive feedback on their own activities. Strategic learning occurs when students can identify and apply, consciously or unconsciously, the intelligent procedures, processes, skills, and strategies that help them to master the learning material and to transfer these strategies from one situation to another.

Information communications technologies (ICT) are often expected to facilitate knowledge construction (Graesser, Chipman, & King, 2008; Jonassen, 2004; Mayer, 2005a). An important question is how learning environments can be designed to optimally facilitate students’ knowledge construction. Therefore, more work is needed to develop and validate operational models of the cognitive, discourse, and linguistic processes underlying constructive learning. An optimal learning environment may enable pupils to interact with a large repository of virtual reality (gaming) tools and multimodal documents that can be explored and consulted to find new information that helps to construct individual knowledge. Digital assistants equipped with reasoning and dialogue capabilities can be designed to support the learning process. They may help the learner to select the relevant problem-solving method, to use this method to query for domain terms and knowledge, and to conduct completeness and consistency analyses.

A common way to ground learning in meaningful contexts is to anchor the learning experience in an information-rich, coherent, realistic, problem scenario (Leu & Kinzer, 2000). These environments with anchored problem-based learning provide an authentic context for students to identify and define problems, to execute strategies to solve the problems, to specify reasons for attempted solutions, and to observe results. Given the fact that multimedia is expected to facilitate knowledge construction (Mayer, 2005a) an important question is how learning environments can be designed to optimally facilitate students’ knowledge construction. The anchors and subsequent assignments make the learning task more meaningful for the student. An anchor can be seen as a macro-context (e.g., a video, an engaging text, a challenging problem) that introduces a topic and provides a frame of reference for a series of lessons. Taking the assignment as a starting point, the student has to search for the relevant information in large amounts of material available in the Internet. Whenever a relevant source in the vast information repository is selected, the student needs to scan it for relevant content and read what is relevant under tight time constraints. Inferences are made from multimedia, including oral and written text along with pictures to compare and contrast concepts. The next step is to succeed in comprehending the multimedia presentation in line with the original assignment.

1.2. Processes in multimedia comprehension

With respect to multimedia comprehension, the focal question is how students are capable of assigning meaning to various text formats. Research on multimedia comprehension has moved towards models in which cognitive, memory-based views and constructivist views are integrated. The memory-based view considers comprehension as a product of processing of explicitly presented information, whereas constructivist theories emphasize the roles of world knowledge and inferences (Verhoeven & Perfetti, 2008). Taking an integrated view as a starting point for the study of multimedia comprehension, it is important to examine how multimedia processing takes place and how students learn to develop multimedia comprehension skills. Static or animated pictures may either facilitate or inhibit students’ comprehension of multimedia text depending on external and internal conditions of learning (Schnitz & Rasch, 2005). Accordingly, a deep analysis of the integration process is essential. The comprehension of multimedia demands specific strategies of information utilization and is highly vulnerable to goal competition and task difficulty (De Stefano & LeFevre, 2007).

The basic question is how a mental simulation of the referential situation is built up on the basis of the verbal and pictorial information in the multimedia presentation. The cognitive theory of multimedia learning (Mayer, 2005b) is based on the idea that there are separate processing systems for both kinds of information. More specifically, the theory assumes an auditory—verbal channel and a visual—pictorial channel within working memory, both with limited processing capacities. Fig. 1 displays the components of multimodal text and picture processing graphically. Contrary to the cognitive theory of multimedia learning, the integrative model of text and picture comprehension assumes channels on two different levels. On the perceptual level, the model includes sensory channels (such as an auditory channel and a visual channel), and on the cognitive level, it assumes representational channels, namely a descriptive channel and a depictive channel in working memory (Schnitz, 2005).

Comprehending written text can be seen as a secondary language process derived from comprehending spoken language. The comprehension of verbal information involves the identification of words, the processing of sentences and the construction of text models along the lines as described before. The comprehension of pictorial information involves the construction of pictorial models. According to Paivio’s (1986) dual coding theory, the two coding systems are supposed to be interconnected. It has also been found that pictorial information can help in comprehending complex expository text (Marcus, Cooper, & Sweller, 1996). Based on observed modality effects, for example, Mayer argues that a higher quantity of learning (i.e., recall of facts) and quality of learning (i.e., capacity to transfer what is learned to new situations) are attained when text and pictures are presented in an auditory—visual mode as opposed to a visual—visual mode (cf. Schnitz, 2005). The additive learning effect of pictures accompanying oral or written texts is referred to as the multimedia effect by Mayer (2005b). Ginn (2005) found in a metanalysis an overall robustness of this modality effect. In more recent studies, an added learning value of interpretational pictures in multimedia text comprehension was
demonstrated and indicated that pictures can also help to clarify difficult text (Mayer, Fennell, Farmer, & Campbell, 2004).

In order to comprehend hypermedia, the reader must also know how to navigate information pages by making selections among the links available. For hypermedia comprehension, the student must combine the meaning of each unit with the message accumulated up to that point on the basis of prior units and their mutual links. Knowledge integration involves a large number of component skills that are not always adequately covered in instructional design. One of these skills refers to the chunking of multiple information elements into a single unit or into cognitive schemas that can subsequently be automated and stored in long-term memory. The information that becomes integrated may stem from different information sources such as text and pictures. These integrative processes may impose high working memory load on the student’s working memory (Paas, Tuovinen, Tabbers, & Van Gerven, 2003). When the process of knowledge integration is collaborative, there is the possibility to divide the cognitive load into more or less even parts, although the students need to keep track of multiple points of view within the collaboration (e.g., Kirschner, Paas, & Kirschner, in press). Social interaction may help students become better at demarcating different concepts and meanings within a certain theme, to take into account divergent views and also misconceptions, and to make distinctions between subjective and objective knowledge (Mercer, Wegerif, Dawes, Sams, & Fernandez, 2008).

1.3. A cognitive load perspective

Cognitive load can be defined as the load that performing a task imposes on the learner’s cognitive system (Paas & van Merrienboer, 1994; Sweller, 1994). Fig. 2 displays the components which are involved in cognitive load theory (CLT). According to this theory, learning processes that lead to knowledge construction and automation are determined by the goal, the required mental representations, the learner’s inventory of cognitive schemata and processing strategies. Performance of learning tasks and the associated learning processes impose a cognitive load on the learner’s working memory. Central to the cognitive load theory is the distinction between intrinsic load, which is due to the task, and extraneous load, which is due to sub-optimal instruction. Intrinsic load involves element activity which is determined by the nature of the task demands in relation to the expertise and motivation of the learner. Instructional design may result in extraneous load (which is ineffective for learning) and in germane load (which is effective for learning). Extraneous cognitive load is defined as unnecessary extra load due to poorly designed instruction. Germiane load is defined as load that contributes to learning such as, for instance, self-explanations.

Cognitive load theory focuses on how constraints of working memory have to be taken into account in order to optimize learning processes. Working memory can be differentiated into various subsystems (Baddeley, 2002, 2003; Baddeley, Gathercole, & Papagno, 1998; Baddeley & Hitch, 1974). Baddeley’s model of working memory involves two basic components, in which phonological or visual information is briefly retained, namely the phonological loop and the visuo-spatial sketchpad. The processing of phonological information is thought to have an inner rehearsal aspect (the articulatory loop) which allows the phonological information needed for the process of language comprehension to be retained longer in memory. The visuo-spatial sketchpad is assumed to store visuo-spatial information from visual perception of real world scenarios or pictures and graphics. A third more central aspect of working memory is the central-executive system which plays a more active role in determining how information is processed. 

Fig. 1. Processes in multimedia comprehension.

Fig. 2. Aspects of cognitive load theory.
executive system which constitutes the control mechanism to coordinate the storage and processing of basic information. Executive control enables the learner to structure information in the form of combinations of elements in long-term memory, so-called schemas (Sweller, 1988). Schemas are defined as the cognitive structures which make up the knowledge base. Over a lifetime of learning, such schemas build a growing body of knowledge and gradually transform novice learners into experts. However, schema acquisition is dependent on working memory and on the extent to which cognitive load is aligned with its cognitive capacity. Cognitive load theory is concerned with techniques of adapting cognitive load by optimizing the use of working memory capacity in order to facilitate changes in long-term memory associated with schema acquisition. Cognitive load theory has many implications for instructional design. According to the classical view of the cognitive load theory, learning materials should keep the students’ extraneous cognitive load at a minimum and germane load at a maximum during the learning process. For instance, it has been found that the cognitive load of instructional materials can be reduced by using goal-free problems (Paas, Camp, & Rikers, 2001) or worked examples (Van Gog, Paas, & Van Merriënboer, 2006), or by making mental integration easier through simultaneous availability in working memory. A recent re-conceptualization of cognitive load theory by Schnotz and Kürschner (2007) suggests that germane load should not simply be maximized, but rather adapted to the intrinsic load of the learning task within the constraints of working memory.

An important question is how cognitive load influences knowledge construction in interactive learning environments. Web-based learning involves specific digital literacy skills in order to benefit from online information processing tasks (cf. Wiley & Schooler, 2001). One obvious concern is the cognitive load these tasks presuppose (van Gog & Paas, 2008). Students come to the learning situation with a limited working memory that needs to coordinate semi-independent processing units for verbal and pictorial information and to integrate it with prior knowledge stored in long-term memory (Mayer, 2005a). The question is how this dual-channel processing architecture helps students to acquire new knowledge: how can cognitive overload be prevented during processes of document comprehension and knowledge integration?

2. The present special issue

The present special issue examined the impact of cognitive load factors in interactive knowledge construction, such as adopting goals and taking perspective, availability of prior knowledge, effects of interactive animation, environmental support and possibilities of collaboration. How do these factors and different characteristics of the learner influence interactive knowledge construction? The six articles in this special issue addressed these aspects of interactive knowledge construction in different ways.

In the first article, Amadieu, van Gog, Paas, Tricot, and Mariné (this issue) investigate the effects of prior knowledge and concept map structure on disorientation, cognitive load, and learning. In this study, they explored the effects of prior knowledge and concept map structure on disorientation, cognitive load, and learning from non-linear documents on “the infection process of a retrograde virus” (HIV). The added value of combining different measurement techniques was also examined, particularly the use of overall subjective ratings of disorientation and cognitive load, as well as detailed analyses of eye movement and navigation data. Two types of map structure were implemented: a hierarchical structure and a network structure. The hierarchical structure was expected to guide learners’ attention towards the main concepts and their semantic relationships (concepts belonging to the same topic), and to guide their navigation path in a highly coherent way (e.g., topic coherence or temporal—causal coherence). An expertise reversal effect was hypothesized. The results showed that learners with limited prior knowledge gained equal factual knowledge from the two types of maps, gained more conceptual knowledge from the hierarchical map structure, and had to invest less mental effort in the post-test after learning with this map structure. High prior knowledge learners, on the other hand, gained more factual knowledge from the hierarchical map structure, and gained equal conceptual knowledge from both map structures. Low prior knowledge learners experienced higher disorientation during learning with the network map structure than with the hierarchical map structure, whereas no differential effect of map structure was found for high prior knowledge learners. Both groups of learners invested less mental effort in processing the hierarchical map structure. The eye tracking and navigation data provide more detailed insight into these findings.

In the second article, Scheiter, Gerjets, Vollmann, and Catrambone (this issue) examine the impact of learner characteristics on strategies of information utilization, cognitive load, and learning outcomes in hypermedia learning. Students were first distinguished according to their learner characteristics by means of a cluster analysis. It was expected that there would be distinct groups, whose profiles are not determined only by differences in prior knowledge, but also by differences in self-regulation abilities, preferences for amount of instruction, and epistemological beliefs. In addition, it was analyzed how these learner characteristics profiles would affect strategies of using different example formats in a hypermedia environment, the experienced cognitive load, and problem-solving performance. In line with prior research, it was assumed that learners with a more favorable pattern of learner characteristics (i.e., a higher level of prior knowledge, better self-regulatory abilities, and preferences for receiving large amounts of instruction, and more complex epistemological beliefs) would show more effective example utilization strategies (i.e., select modular examples more frequently, choose elaborated and incomplete examples only if necessary, and select examples to conduct helpful comparisons within and across problem categories), would experience less cognitive load during learning, and show better problem-solving performance. Based on the data of 79 students, five groups of students were identified according to their learner characteristics. Further analyses showed that learners with more favorable characteristics tended to show...
In the third article, Kalyuga (this issue) considers the process of knowledge elaboration from the perspective of CLT. The theory assumes that the available knowledge structures perform executive (organizing and guiding) functions in complex learning processes. This paper analyzes some cognitive load-related instructional implications of this assumption; it suggests adaptive learning environments based on diagnostic assessment of current levels of learner knowledge as effective means for tailoring knowledge elaboration processes to changing characteristics of individual learners and developing complex cognitive skills. On the basis of an extensive review of recent studies, it is concluded that the knowledge base in learner long-term memory provides executive guidance in the process of knowledge elaboration. Accordingly, the role of external instructional guidance could be described as providing a substitute for missing LTM knowledge structures in a schema-based framework for knowledge construction and elaboration. Furthermore, it is argued that adaptive learning environments based on rapid diagnostic methods could provide instructional support at different stages of knowledge elaboration in order to optimize cognitive load. Continuous balancing of executive function is seen as essential for optimizing cognitive load by presenting required guidance at the appropriate time and removing unnecessary redundant support as learner proficiency in a domain increases.

In the fourth article, Rasch and Schnottz (this issue) explore how the use of interactive pictures in multimedia environments affects the outcomes and the efficiency of learning and to what extent these effects can be generalized to different visualization formats and learning tasks. Based on a theoretical framework regarding learning from text with interactive and non-interactive pictures combined with different visualization formats, an experiment was conducted. The experiment firstly investigated the effects of adding pictures to texts on learning outcomes as well as on learning efficiency; secondly, it analyzed the specific effects of interactive pictures as compared to non-interactive pictures; and, thirdly, the experiment investigated whether the visualization structure of pictures affects not only the structure of mental models, but also influences the effects of interactivity. One hundred university students were randomly assigned to five experimental conditions: two groups with text and interactive pictures (combined with one out of two different visualization formats), two groups with text and non-interactive pictures (combined with one out of two different visualization formats), and one group with text only. Adding pictures to texts did not result in higher learning outcomes, but was also not harmful for learning. However, participants learned significantly more efficiently when they did not use text and pictures, but only text. In other words, processing of pictures required more time without being beneficial for learning. Participants showed higher learning outcomes after learning with interactive pictures with one kind of task, but not with the other kind of task. Results further indicated that the format of visualization affected the structure of mental models. Whereas the visualization format had a significant influence on the learners’ use of interactivity, this effect was not mirrored in significant differences in terms of learning outcomes. The authors discuss their findings with regard to the role of learning time (i.e., students can compensate reduced learning efficiency by longer learning times in self-paced learning), the role of replacements of information sources (i.e., learners can replace text processing by picture processing) and the different functions of interactive pictures (interactive pictures can have an enabling effect or a facilitating effect) in the process of learning.

In the fifth article, Segers and Verhoeven (this issue) examine multimedia comprehension in primary school children. In the past decade, the study of multimedia-based knowledge construction has started to become an area of vivid research. However, to a large extent the focus was on students in secondary schools and beyond. Research on the capabilities of primary school children in multimedia learning so far is extremely scarce (cf. Kuiper, Volman, & Terwel, 2005). In this study, children’s learning in a sheltered Internet environment, using so-called WebQuests in elementary school classrooms in the Netherlands was investigated. A WebQuest is an assignment presented together with a series of web pages to help guide children’s learning. The purpose of the present study was to further explore children’s learning within a sheltered learning environment. In a quasi-experimental design, positive effects of working in a sheltered learning environment were found. The sixth grade boys studied here benefited in particular from working in a more sheltered learning environment (i.e., the closed search condition) while the sixth grade girls showed more or less equivalent learning gains in the closed-versus free-search conditions within the sheltered environment. Both the linguistic and cognitive capacities of the children were found to play a role in their learning gains with the higher ability children generally learning more. The quality of the children’s WebQuest work was found to correlate with not only their cognitive and linguistic abilities but also with their knowledge test scores at the pre-test. A difference in the quality of the writing for the two conditions was evidenced with the language quality being higher in the free-search condition, but this was not related to a difference in learning gain. Furthermore, it was found that the children’s motivation to learn from the Internet did not change as a result of the intervention in the closed-search condition, but might diminish in the free-search condition. Their perceptions of their own computer skills showed significant gains.

In the sixth and final article, Moreno (this issue) explores the construction of knowledge with an agent-based instructional program for college students. Following an experimental design, she makes an attempt to compare processes of cooperative and individual meaning making. College students learned about botany using an agent-based instructional program with three learning approaches: individual approach, jigsaw approach, or cooperative approach. The results showed that students who learned with the cooperative approach perceived the learning experience as more interesting than those who learned with the individual or the jigsaw approach,
a finding that is consistent with the literature comparing cooperative and individual learning methods. It was also found that the cooperative approach group produced only descriptively higher retention and transfer scores than the individual approach group. This finding runs at odds with the small, yet significant, advantage of learning in small groups with technology. It is interesting to note that students in the jigsaw approach group perceived the learning experience to be more difficult than those in the individual approach group and were less able to transfer what they learned to solve novel problems as compared to the cooperative approach and individual approach groups, suggesting that the jigsaw method may not be an effective approach to agent-based multimedia learning. Furthermore, the analysis of students’ statements showed that the jigsaw approach promoted a larger number of retention and metacognitive statements whereas the cooperative approach promoted a larger number of elaboration statements. This finding seems to indicate that the jigsaw approach participants focused more on transmitting and receiving information and regulating their progress towards the learning goals than on elaborating on the instructional materials. To conclude, no differences among treatments on retention were evidenced. Students in the jigsaw approach group reported higher cognitive load during learning than students in the individual approach group, scored lower on a problem-solving transfer test than students in the cooperative approach and individual approach groups, and were less likely to produce elaborated explanations and co-construct knowledge with their peers than students in the cooperative approach group. The cooperative approach group reported higher situational interest than the jigsaw approach and individual approach groups.

In the two commentaries, the contents of this special issue are discussed. Rouet (this issue) and Goldman (this issue) present concise commentaries on the research-based articles being presented and a short perspective on research on cognitive load in interactive knowledge construction in the future. Rouet (this issue) discusses the output of the present issue in terms of the subject, task and environmental characteristics being involved. Moreover, he emphasizes the need to control the learners’ level of familiarity with task setting and environmental features with a view to optimal learning outcomes. In a similar vein, Goldman (this issue) claims that the papers in this issue make evident that one and the same learning environment can be differentially demanding and successful, due to the individual characteristics of the learner. Therefore, she warns theories of instructional design to become more adaptive taking into account the nuances of interactions among learners, tasks and instructional support levels.

3. Conclusion

From the present issue it can be concluded that cognitive load has a great impact on interactive knowledge construction. The six research-based articles make clear that varying constraints of working memory need to be taken into account in order to optimize learning processes in interactive knowledge construction. First of all, learning outcomes turn out to be dependent on personal characteristics such as prior knowledge, motivation and perspective-taking. Furthermore, learning outcomes appear to be mediated by task demands, which are the result of instructional design. Concept map structures and interactive animations can be seen as examples of manipulations of instructional design which have been shown to impact the outcome of learning processes. Finally, the success of learning turns out to be clearly related to environmental factors such as interactivity, locus of control and opportunities for collaboration. It is important to note that the research reported also shows that personal, task and environmental factors interact, which may urge for differential instructional measures.

To be able to implement learning environments that optimally facilitate students’ learning, an attempt should be made to develop and validate operational models of the cognitive processes underlying knowledge construction. Therefore, there is an urgent need for fine-grained experimental studies in which the precise impact of specific aspects of cognitive load on learning in varying conditions of instructional context is examined. The use of advanced methods such as eye tracking and brain modeling techniques may shed more light on the functional anatomy and temporal dynamics of cognitive processes which are involved in interactive knowledge construction. Besides, it is important to conduct naturalistic studies in which the interactions among learners, tasks and instructional support levels in actual classrooms are object of investigation. In order to optimize cognitive load, adaptive learning environments should be implemented in which task demands and instructional support levels are attuned to the expertise and memory capacities of the individual learner (see, e.g., Salzen, Paas, & Van Merrienboer, 2006).

References


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