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Guest editorial

Cognitive load theory: implications of cognitive load theory on the design of learning

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Abstract

Cognitive load theory (CLT) can provide guidelines to assist in the presentation of information in a manner that encourages learner activities that optimise intellectual performance. It is based on a cognitive architecture that consists of a limited working memory, with partly independent processing units for visual and audio information, which interacts with an unlimited long-term memory. According to the theory, the limitations of working memory can be circumvented by coding multiple elements of information as one element in cognitive schemata, by automating rules, and by using more than one presentation modality. This special issue consists of six articles from four countries and three continents on the instructional implications of CLT. The articles cover presenting instructional techniques for increasing germane CL in studying worked examples (van Merriënboer, Schuurman, De Croock, & Paas), effects of example elaboration training on decreasing cognitive interference and overload (Stark, Mandl, Gruber, & Renkl), CLT-based instructional design when dealing with very high element interactivity material (Pollock, Chandler, & Sweller), effects of worked examples on CL in older learners (Van Gerven, Paas, & Schmidt), a cognitive theory of multimedia learning (Mayer & Moreno), and the use of external representations to help manage CL in Computer Supported Collaborative Learning environments (Van Bruggen, Kirschner, & Jochems). © 2001 Elsevier Science Ltd. All rights reserved.

1. Why this special issue?

In educational contexts there is a growing call for competency-based education. Competencies can be construed as abilities that enable learners to recognize and define new problems in their domain of study and — future — work as well as solve

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these problems (Kirschner, van VIlsteren, Hummel, & Wigman, 1997). According to Keen (1992), competencies refer to the ability to operate in ill-defined and ever-changing environments, to deal with non-routine and abstract work processes, to handle decisions and responsibilities, to work in groups, to understand dynamic systems, and to operate within expanding geographical and time horizons. In other words, competencies are a combination of complex cognitive and higher-order skills, highly integrated knowledge structures, interpersonal and social skills, and attitudes and values. Acquired competencies enable learners to apply these skills and attitudes in a variety of situations (transfer) and over an unlimited time span (lifelong learning) (van Merriënboer, 1999; see also Fletcher, 1997a,b; Spencer & Spencer, 1993).

The design of education based on a competency based paradigm is fundamentally different from what instructional designers are used to doing. The acquisition of the necessary complex cognitive skills added to the requirement that the learners can then apply those skills in new situations and new domains (far transfer) asks much from learners. To design, development, and implement such education — in which cognition, meta-cognition and transfer are the most important variables — requires us to better understand and make use of the possibilities and take into account the limitations of the human mind. Cognitive load theory (CLT) may offer instructional designers a tool for achieving this goal.

The six contributions to this special issue form a good overview of both what CLT is as well as what the effects of this theory is on instructional design for effective and efficient learning. In this article I will first attempt to construct a background for the reader of the fundamental elements in CLT. This will be followed by a description of the six articles in the issue. Finally, the possible consequences of CLT research on instructional design will be discussed.

2. Cognitive architecture: memory and schemas

Short-term or working memory is what you are using at this very moment to process this text (stimuli have entered your sensory register through attention and recognition). You use it for all of your conscious activities and it is the only memory that you can monitor. Everything else — content and function — is concealed until brought into working memory. A problem, especially for instructional designers, is that it is limited to about seven items or elements of information at any one time (Miller, 1956; Baddeley, 1992). Furthermore, because working memory is also used to organise, contrast, compare or work on that information, you probably can only process two or three items of information simultaneously as opposed to merely holding that information. Finally, working memory is seen not as one monolithic structure, but rather a system embodying at least two mode-specific components: a visuo-spatial sketchpad and a phonological loop co-ordinated by a central executive.

Long-term memory (LTM) is, in contrast, what you use to make sense of and give meaning to what you are doing now. It is the repository for more permanent knowledge and skills and includes all things in memory that are not currently being used but which are needed to understand (Bower, 1975). Most cognitive scientists believe

that the storage capacity of LTM is unlimited and that is a permanent record of everything that you have learnt. You are not directly conscious of LTM. Awareness of its contents and functioning is filtered through working (conscious) memory.

Human cognition, thus, places its primary emphasis on the ability to store seemingly unlimited amounts of information including large, complex interactions and procedures in LTM. Human intellect comes from this stored knowledge and not from long, complex chains of reasoning in working memory which is incapable of such highly complex interactions using elements not previously stored in LTM. It follows, that instruction (and instructional design) that require learners to engage in complex reasoning processes involving combinations of unfamiliar elements are likely to present problems and not work well. Instruction, thus, must consider how is this information stored and organised in LTM so that it is accessible when and where it is needed.

According to *schema theory*, knowledge is stored in LTM in schemata. Schemata categorise information elements according to how they will be used (Chi, Glaser, & Rees, 1982). A schema can hold a huge amount of information, yet is processed as a single unit in working memory. Schemata can integrate information elements and production rules and become automated, thus requiring less storage and controlled processing. Skilled performance consists of building increasing numbers of increasingly complex schemas by combining elements consisting of lower level schemas into higher level schemas.

Schemas can also reduce *working-memory load*. Although working memory can process only a limited number of elements at a time, the size, complexity, and sophistication of elements is not. A schema can be anything that has been learnt and is treated as a single entity. If learning has occurred over a long period of time, a schema may incorporate a huge amount of information. In summary, schema construction aids the storage and organisation of information in long-term memory and reduces working memory load.

3. Cognitive load

CLT assumes a limited working memory connected to an unlimited long-term memory (Baddeley, 1986). As a result of this limitation instruction should be designed such that working memory is capable of processing the instruction (i.e. the information that constitutes the instruction). CLT, thus, is concerned with the limitations of working-memory capacity and the measures that can be taken to promote learning, that is the construction of schemata, by imposing adequate levels of CL. In other words: How can the instructional designer assure that the limits of the learner's working memory load are not exceeded when he or she is processing instruction?

Both causal and assessment factors affect CL (Paas & van Merriënboer, 1993; see Fig. 1). Causal factors can be characteristics of the subject (e.g. cognitive abilities), the task (e.g. task complexity), the environment (e.g. noise), and their mutual relations. Assessment factors include mental load, mental effort, and performance as

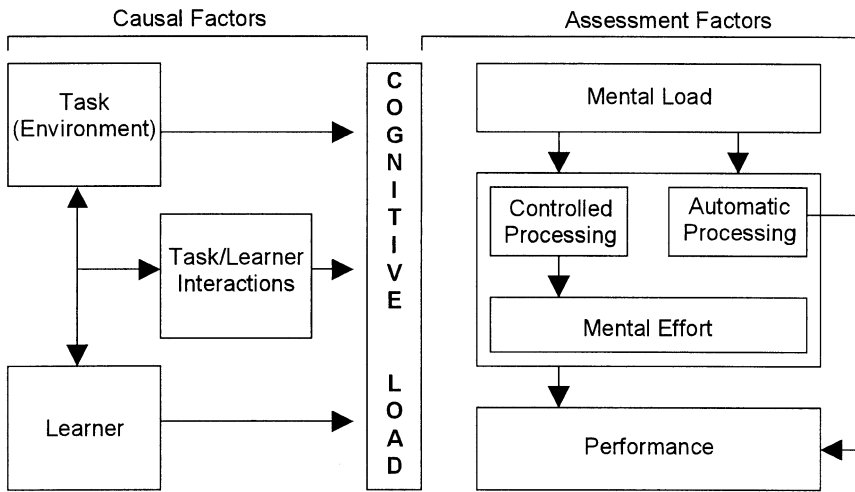


Fig. 1. Factors determining the level of cognitive load.

the three measurable dimensions of CL. Mental load is the portion of CL that is imposed exclusively by the task and environmental demands. Mental effort refers to the cognitive capacity actually allocated to the task. The subject's performance, finally, is a reflection of mental load, mental effort, and the aforementioned causal factors.

Working memory load is affected by the inherent nature of the material (intrinsic CL) and by the manner in which the material is presented (extraneous and germane CL). The following is a short explication of these three aspects of CL. The articles contained in this issue highlight relevant specific aspects in detail.

Learning, reflected by performance change, requires working-memory capacity. That is, it imposes a *germane CL* on the learner (Sweller, van Merriënboer, & Paas, 1998). Germane CL is required for the construction and storage of schemata into long-term memory. The construction of adequate and rich schemata is especially important in complex learning tasks where it will require more effort, because the elements contained by the to-be-learned material are highly interconnected (see, for example, the article in this issue by Pollock et al.). This is referred to as *intrinsic CL*, which is the portion of load that is imposed by the intrinsic characteristics of the task or subject matter. According to CLT the limitations of working memory are rarely taken into account in conventional instruction. Conventional instructions tend to impose an *extraneous CL* on working memory, whereas learning something requires shifting from extraneous to germane CL.

CLT states that the instructional interventions cannot change the intrinsic CL because this is *ceteris paribus* intrinsic to the material being dealt with. Extraneous and germane CL, however, are determined by the instructional design (Sweller, 1994). Although both can be altered by instructional interventions, extraneous CL is the effort required to process poorly designed instruction, whereas germane CL is the effort that contributes, as stated, to the construction of schemas. Appropriate

instructional designs decrease extraneous CL but increase germane CL, provided that the total CL stays within the limits. A salient problem here is that, as is discussed in detail in the article by van Merriënboer et al., there is no empirical evidence nor technique which allows us to discriminate between the two. We can only determine what the total CL is and how it has been affected.

CLT has led to the development of a number of instructional formats, including goal-free problems, worked examples and completion problems. An exhaustive overview of CLT-based instructional formats and their empirical base is given by Sweller et al. (1998).

4. Germane cognitive load and instructional design

CLT research has primarily studied instructional designs meant to decrease extraneous CL. Recently, some studies have been conducted in which germane CL was increased when it was considered directly relevant to schema construction (Sweller, 1999). The basic assumption is that an instructional design that results in unused working memory capacity because of a low intrinsic CL imposed by the instructional materials and/or low extraneous CL due to appropriate instructional procedures may be further improved by encouraging learners to engage in conscious cognitive processing that is directly relevant to schema construction. Clearly, this approach can only work if the total CL of the instructional design (intrinsic CL+extraneous CL+germane CL) is within working memory limits. This is the new frontier of instructional design.

5. The contributions

All of the contributors to this special issue present either theoretical or empirical studies relating to CLT and its implications for instructional design.

Van Merriënboer, De Croock, Schuurman, and Paas describe three experiments to test guidelines to instructional design which come from CLT with respect to their effects on both extraneous and germane CL as well as on learning results and training efficiency. CLT, on the one hand, states that extraneous CL is decreased in instructional situations where learners can use strategies other than weak-method problem solving methods such as means–ends analysis (e.g. in conventional problems). On the other hand, instructional methods such as worked out examples (WOEs) which decrease extraneous CL and increase germane CL may lead to superficial processing of information. A possible remedy for this is to present these WOEs in such a way that students are ‘prompted’ to compare and contrast the procedures in the WOEs (the greater the difference between WOEs, the higher the *contextual interference*). Their first experiment studies the decrease of extraneous CL by the use of *completion problems*, the guideline being that CL extraneous to the construction of cognitive schemata should be minimised. They compare completion problems, in which learners have to complete partial solutions to problems, to conventional problems, in

which learners have to generate full solutions. Completion problems decrease CL during training and have a zero or positive effect on transfer test performance. The second experiment studied the increase of germane CL by the use of high contextual interference (HCI), the guideline being that germane CL that is directly relevant to schema construction should be optimised. Here, practice schedules with high and low contextual interference (HCI and LCI) are compared. HCI increases the CL during training (as predicted) whereby the learners used more time and more mental effort during instruction, but also resulted in increased retention and transfer performance. A final experiment studied the *redirection of attention* by simultaneously decreasing extraneous CL and increasing germane CL. It combines both earlier stated guidelines in a 2×2 factorial experiment with the factors problem format (completion vs. conventional) and contextual interference (HCI vs. LCI). They hypothesise that redirecting attention from extraneous to germane processes will improve training efficiency, i.e. positively affect the balance between CL during training and transfer test performance. In support of this hypothesis, they found that the completion-HCI group shows highest training efficiency. But transfer test performance for this group was disappointing. The results are discussed in relation to the learners' task involvement and the way in which HCI was made operational in combination with completion problems.

Stark, Mandl, Gruber, and Renkl study the influence of learning behaviour on the success of *example-based learning* in order to draw consequences from this for instructional practice. Based on an earlier study on learning with WOE's in the domain of accounting they analyse the effects of example-elaboration training on learning behaviour. This intervention, as in the study by van Merriënboer et al. described above, hopes to circumvent the shallow processing that WOE's might induce. In a further step, different ways of dealing with WOE's (elaboration profiles) are identified and related to the subsequent learning success (both cognitive and meta-cognitive) and to the learners' mental effort. Finally, they attempt to explain the formation of different elaboration profiles by the learners' specific characteristics (prior knowledge, domain interest, and tolerance of ambiguity). They were able to show that example-elaboration training had a positive effect on learning behaviour. Two types of successful learning with examples could be described. Subgroups of learners with different elaboration profiles differed in their mental effort and in the extent of their tolerance of ambiguity, but not in their prior knowledge or their domain-specific interest. This might be due to the fact that prior knowledge can lead to either more elaboration or less elaboration. The authors describe this problem in their article. A more marked tolerance of ambiguity concurred with a stronger mental effort and resulted in successful, meta-cognitive learning behaviour. To enhance the effectiveness of the learning method investigated they recommend special activating means (i.e. in the form of incomplete examples), that should be supported by additional explications, for subgroups of learners.

Pollock, Chandler, and Sweller describe four experiments generated by CLT examining a novel interpretation of the theory. If it is the case that working-memory is limited, it might be the case that first learning non-interacting, isolated aspects of a domain (vocabulary or chemical elements) before learning interacting, related aspects

(syntax or balancing chemical equations) could reduce cognitive overload and lead to better learning, better application and increased transfer. The experiments examine, thus, an alternative approach to instructional design which have the goal of promoting schema construction to foster understanding. A two-phase mixed method learning approach was developed and compared with conventional instruction in experiment 1 with novices in a subject-matter domain and with learners more knowledgeable in the domain in experiment 2. Initially, with the mixed method approach, the element interactivity of complex material was artificially reduced by presenting the material as isolated elements of information that could be processed serially, rather than simultaneously, in working memory. In the second phase of instruction, all the information for understanding (i.e. also the interacting elements) was presented. The conventional group was simply presented with all the information for understanding in both phases 1 and 2. Although a possible consequence of artificially reducing the element interactivity of material may be an initial decrease in a student's capacity for understanding, they hypothesise that over the longer term it would lead to an increase in learners' understanding. The experiments provide powerful evidence that for certain groups of learners, information is better learnt through the *mixed instructional method* and that for all groups both the instructional efficiency (based on mental effort and performance) and the learning efficiency (based on instruction time and performance). Evidence is also provided in support of the proposal that *schema construction* is the mechanism underlying the success of the mixed instructional method. To determine whether the differences found were due to the nature of the content and goal of the materials (heavy emphasis on procedural learning), two new experiments — analogous to the first two experiments — were carried out where the emphasis now was on conceptualisation.

Van Gerven, Paas, and Schmidt take the problem of CLT and its repercussions for instructional design a step further. Life-long learning is one of the most important aspects of competence based education. What is taught today, at least with respect to the content of a domain, is out-of-date tomorrow. If we are to continue learning throughout our lives, then instructional design must take into account the effects of ageing on that learning and on the fundamentals of cognitive psychology and learning theory. Ageing may decrease working-memory capacity, decrease processing speed and/or decrease the learner's ability to inhibit irrelevant or distracting information. If this is so, then this cognitive ageing would greatly impede the ability of elderly people to acquire complex skills. Van Gerven et al. examine whether the claim that CLT-based training formats meet the cognitive abilities of elderly learners particularly well, by presenting information in a highly efficient manner, holds up. By making an optimal use of the 'remaining' cognitive resources, learning can be enhanced. This article in this issue presents a study aimed at the efficiency of WOE as a substitute for conventional practice problems in training the elderly. According to CLT, studying worked examples is a more efficient means of training complex skills than, solving conventional problems. As predicted, the results showed that the training efficiency of worked examples is higher than the training efficiency of conventional problems in that less training time and CL leads to a comparable level of performance.

Mayer and Moreno present a cognitive theory of *multimedia learning* which draws on dual coding theory, CLT, and constructivist learning theory. Based on the theory, principles of instructional design for fostering multimedia learning are derived and tested. The *multiple representation* principle states that it is better to present an explanation in words and pictures than solely in words. This proved to be the case when a condition with animation plus narration proved more effective than narration alone. The *contiguity* principle holds that it is better to present corresponding words and pictures simultaneously rather than separately when giving a multimedia explanation. This proved to be the case and appears to validate that working memory has distinct and additive visuo-spatial registers and auditory registers as well as to lend credence to the split-attention hypothesis that either successive or spatially separated information increases extraneous CL. The *coherence* principle posits that multimedia explanations are better understood when they include few rather than many extraneous words and sounds. This too was born out with the results showing that concise materials led to better learning than embellished materials. The *modality* principle states that it is better to present words as auditory narration than as visual on-screen text. Again this proved to be the case since animation plus audio (both sensory as well as spatial split-attention) proved better than animation plus text. Finally, the *redundancy* principle which holds that it is better to present animation and narration than to present animation, narration, and on-screen text (where the last two are redundant) proved to be true. This research presents clear and compelling guidelines for instructional design for multimedia messages based upon a cognitive theory of how learners process multimedia information.

Finally Van Bruggen, Kirschner, and Jochems present a model for applying CLT to the design of computer supported collaborative learning environments using external representations to support the argumentation process. Computer-supported collaborative learning (CSCL) environments, in particular environments where students share external representations, are discussed as an interesting area to applications of CLT. These environments share a number of characteristics that will induce considerable CL. Their article reflects on characteristics of CSCL environments and external representations and the research opportunities they offer to CLT. They argue that CLT can contribute to the understanding of CSCL by pinpointing situations in which high levels of CL are generated. CLT also raises a number of particular issues: from a CLT point of view, studying of worked out external representations may lead to better learning outcomes than (co)-construction which is the standard mode of operation in CSCL. The *ontology* and *specificity* of the representational scheme used are crucial factors, since they define what can be expressed and how much room for interpretation is left in the representation. CLT may help identify mismatches between representational schemes and execution of (sub)tasks. CLT has led to a number of recommendations on the integration of diagrammatic and textual information. They relate this to discussion and chat facilities in CSCL and describe how these can be more firmly anchored in the external representation.

6. Consequences of CLT research on instructional design

CLT clearly offers promising perspectives on how instructional materials for acquiring complex cognitive skills and competencies can and should be designed. However, the theory is not as clear cut as it may appear. Looking at the six articles, a number of questions arise. I do not pretend to be complete here, but rather to offer a number of salient questions or points of interest to stimulate the reader to look more closely at the articles and to help them to define relevant fields of study with respect to CLT. Noteworthy, in my opinion is:

1. What are the effects of spatial, temporal and sensory split attention on the clear cut results of Mayer and Moreno?
2. Could the redundancy effect as described by Mayer and Moreno be the reason that Pollock et al. found that non-integrative (mixed-phase) presentation of information proved better than two presentations of integrated materials?
3. What are the effects of the five principles presented by Mayer and Moreno on CL? They use CLT (along with dual-coding and constructivist learning theory), but do not measure either the CL induced nor the mental effort needed by the participants in their studies.
4. Is intrinsic CL really a fixed quality or is it also affected by the causal factors described here and in the article by Van Bruggen et al.?
5. What is the role of prior knowledge with respect to CL and the instructional design procedures which are derived from CLT? Stark et al. state: On the one hand learners with deficient prior knowledge — provided they recognise their deficits as such — may work through example information more deeply and also more intensively concerning meta-cognitive control with learning progress from this intensive analysis. On the other hand, if learners have problems of understanding caused by a lack of prior knowledge which they cannot overcome, they may be led to resign themselves to this and exhibit rather superficial, passive example elaboration. Which is the case?
6. Van Merriënboer et al. have all of their participants study for a fixed amount of time and measure the differences in the number of problems covered during the study period. Pollock et al. allow students to study freely and measure true study time. How would participants have fared in the former study if either the number of problems was fixed or if allowed to study freely until they felt that they had learnt enough? Students (either in schools or in continuing education situations) are strapped for time and it would clarify a number of issues if training efficiency was not calculated but was based upon real study time.
7. Finally, with respect to Van Bruggen et al. an interesting field of study would be if (joint) studying worked examples and completion problems of external representations in CSCL environment show the same positive effects on learning outcomes as found with more traditional instructional material? Can the modality effect as described by Mayer and Moreno be exploited in synchronous CSCL environments, and under what conditions? And finally, can we apply CLT to

create more firmly anchored and integrated discussions in CSCL environments and do they lead to better learning outcomes?

At the end of this issue two referees, Prof. Dr. Martin Valcke from the University of Gent (Belgium) and Dr. Maria Bannert from the University of Koblenz-Landau (Germany) will critically discuss the articles and undoubtedly offer further reaching insights into the subject area.

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