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Cognitive Load Theory: Instructional Implications of the Interaction between Information Structures and Cognitive Architecture

FRED PAAS[1,*], ALEXANDER RENKL[2] AND JOHN SWELLER[3]
[1]*Educational Technology Expertise Center, Open University of the Netherlands, 6401 DL Heerlen, The Netherlands;* [2]*University of Freiburg, Freiburg, Germany;*
[3]*The University of New South Wales, Sydney, Australia*
*(*author for correspondence: e-mail: Fred.Paas@ou.nl)*

Within the cognitive load theory research community it has become customary to report theoretical and empirical progress at international conference symposia and in special issues of journals (e.g., *Educational Psychologist* 2003; *Learning and Instruction* 2002). The continuation of this custom at the 10th European Conference for Research on Learning and Instruction, 2003, in Padova, Italy, has materialized in this special issue of *Instructional Science* on the instructional implications of the interaction between information structures and cognitive architecture. Since the 1990s this interaction has begun to emerge as an explicit field of study for instructional designers and researchers. In this introduction, we describe the basics of cognitive load theory, sketch the origins of the instructional implications, introduce the articles accepted for this special issue as a representative sample of current research in this area, and discuss the overall results in the context of the theory.

It is generally accepted that performance degrades at the cognitive load extremes of either excessively low load (underload) or excessively high load (overload) – see e.g., Teigen (1994). Under conditions of both underload and overload, learners may cease to learn. So, whereas learning situations with low processing demands will benefit from practice conditions that increase the load and challenge the learner, learning situations with an extremely high load will benefit from practice conditions that reduce the load to more manageable levels (Wulf and Shea 2002).

Cognitive load theory (CLT; Paas, Renkl and Sweller 2003; Sweller 1988, 1999) is mainly concerned with the learning of complex cognitive tasks, where learners are often overwhelmed by the number of information elements and their interactions that need to be processed simultaneously before meaningful learning can commence. Instructional control of this (too) high load, in order to attain meaningful learning in complex cognitive domains, has become the focus of CLT. The theory suggests that learning happens best under conditions that are aligned with human cognitive architecture.

CLT assumes a cognitive architecture consisting of a working memory that is limited in capacity when dealing with novel information, and that includes partially independent subcomponents to deal with auditory/verbal material and visual/2- or 3-dimensional information. CLT also assumes that limited capacity working memory becomes effectively unlimited when dealing with familiar material, previously stored in an immense long-term memory holding many schemas that vary in their degree of automation. Schemas categorize elements of information according to the manner in which they will be used (e.g., Chi, Glaser and Rees 1982). Skilled performance develops through the construction of increasing numbers of ever more complex schemas by combining elements consisting of lower level schemas into higher level schemas. Schema automation allows those schemas to be processed unconsciously, with consequent working memory implications. Both schema construction and automation can free working memory capacity. Knowledge organized in schemas allows learners to categorize multiple interacting elements of information as a single element, thus reducing the burden on working memory. After extensive practice schemas can become automated, thereby allowing learners to further bypass working memory capacity limitations. From an instructional design perspective, it follows that designs should encourage both the construction and automation of schemas.

Cognitive load theory is concerned with techniques for managing working memory load in order to facilitate the changes in long term memory associated with schema construction and automation. CLT distinguishes between three types of cognitive load: intrinsic, extraneous, and germane. The load is called ‘intrinsic’ if it is imposed by the number of information elements and their interactivity. If it is imposed by the manner in which the information is presented to learners and by the learning activities required of learners, it is called ‘extraneous’ or ‘germane’. Whereas, extraneous or ineffective load is imposed by information and activities that do not contribute to the processes of schema construction and automation, germane or effective load *is* related to information and activities that foster these processes. Intrinsic, extraneous, and germane load are considered additive in that, taken together, the total load cannot exceed the memory resources available if learning is to occur (see, Paas, Tuovinen, Tabbers and Van Gerven 2003).

Kalyuga, Ayres, Chandler, and Sweller (2003) have shown that knowledge of the learner’s level of expertise is of importance for instructional designers to be able to categorize information and activities as intrinsic, extraneous, or germane, and to predict learning outcomes. A cognitive load that is germane for a novice may be extraneous for an expert. In other words, information that is relevant to the process of schema construction for a beginning learner may hinder this process for a more advanced learner. For this reason, instructional designers should integrate target group analysis with knowledge analysis (hierarchical analysis of the material to be learned) when designing instruction, so that the knowledge can be communicated to the learners at the right grain size (Van Merriënboer 1997).

Early work on CLT has made clear that the reduction of extraneous cognitive load, for instance by studying worked-out examples or solving goal-free problems, offers a more effective way of learning complex cognitive tasks than conventional problem solving (Sweller 1988, 1999). Unfortunately, this work on the reduction of extraneous cognitive load has often been misinterpreted to mean that the cognitive load of learners needs to be kept at a minimum during the learning process. Instructional designers need to realize that reducing cognitive load is not necessarily beneficial, particularly in cases where working memory capacity limits are not exceeded and the load is already manageable. As long as the load is manageable, it is not the level of load that matters, but its source. If the load is imposed by mental activities that interfere with the construction or automation of schemas, that is, ineffective or extraneous load, then it will have negative effects on learning. If the load is imposed by relevant mental activities, i.e. effective or germane load, then it will have positive effects on learning.

Cognitive load theory has many implications for the design of learning materials, which must, if they are to be effective, keep the extraneous cognitive load as low as possible during the learning process. However, freeing cognitive capacity by reducing extraneous load is not a sufficient condition for instructional conditions to be effective. At the same time, learning materials should be presented in such a way that germane load is as high as possible. The work by Paas and Van Merriënboer (1994) proved to be an important source of inspiration for the work on germane cognitive load. They showed that learners were only able to deal with, and profit from, the germane load imposed by high variability of practice problems when they studied worked-out examples that reduced the extraneous load. By changing the focus of CLT from reducing extraneous or ineffective cognitive load to optimizing cognitive load, new instructional techniques became available to deal with the problem of increasing germane or effective cognitive load. Evidence of this trend is apparent in a large body of recent work, such as the research on worked examples and self-explanations reported by Renkl, Atkinson, and Große in this issue (see also Renkl, Stark, Gruber and Mandl 1998).

In some learning environments, extraneous load can be inextricably bound with germane load. Consequently, the goal to reduce extraneous load and increase germane load may pose problems for instructional designers. For instance, in nonlinear hypertext-based learning environments, efforts to reduce high extraneous load by using linear formats may at the same time reduce germane cognitive load by disrupting the example comparison and elaboration processes. Gerjets, Scheiter, and Catrambone (2004, this issue) show that it might be better for instructional designers to focus on the reduction of intrinsic load. The reduction of intrinsic load has also become an important goal of instructional theories that stress authentic, real-life learning tasks as the driving force for learning. To prevent the excessive load that is often associated with this type of learning task, simpler tasks omitting some of the interacting elements, can be presented to learners, even though the elimination of those elements may partially compromise full understanding (Pollock, Chandler and Sweller 2002). For example, Van Merriënboer, Kirschner, and Kester (2003) have argued that the intrinsic aspects of cognitive load can be reduced by the scaffold of simple-to-complex sequencing.

This *Instructional Science* special issue continues the theoretical and applied developments associated with CLT. The instructional implications of the interaction between information structures and cognitive architecture are emphasized in eight papers that illustrate many of the emerging research areas in the context of CLT.

Overview of the papers

This special issue begins with an article by Sweller, titled "Instructional design consequences of an analogy between evolution by natural selection and human cognitive architecture" in which he suggests that returning to and strengthening the linkage to evolutionary theory may infuse new ideas and alternative perspectives into ongoing cognitive load research and practice. He draws an analogy between evolution by natural selection and human cognitive architecture, and shows that the processes of random mutation and natural selection can be used as a template to understand human cognition. Using evolutionary epistemology, Sweller explains why our particular cognitive architecture with its missing central executive for dealing with novel information has survived and become adapted to our environment. He argues that cognitive load theory provides techniques for overcoming the claimed lack of an internal, cognitive, central executive when dealing with new material by appropriately structuring information. He further suggests that schemas in long-term memory provide a central executive when dealing with familiar material. The instructional techniques that have been generated by researchers around the globe are summarized in the remainder of the article. Sweller concludes that a combination of evolutionary theory, human cognitive architecture and instructional design may exceed the sum of its parts in terms of generating effective instructional design principles.

The Gerjets, Scheiter, and Catrambone article, “ Designing instructional examples to reduce intrinsic cognitive load: Molar versus modular presentation of solution procedures”, draws on previous research showing the effectiveness of worked examples. They argue that – despite positive effects – most worked examples are structured in a sub-optimal way. The typical presentation of examples focuses on problem-categories, structural features, and the overall solution procedure. Taking all these aspects into account puts heavy demands on working memory and potentially imposes cognitive overload. To this point, such problems were solved by reducing extraneous load. Gerjets et al. propose another instructional strategy that might be better suited for many situations, namely to reduce the intrinsic cognitive load. As a technique to reduce the intrinsic load and to improve learning and transfer performance, the authors propose to use modular worked examples that focus on single solution elements. This “narrowed” focus reduces intrinsic load in comparison to examples that draw the attention to problem categories and their associated overall solution procedures. Several studies are reported that show that such a technique leads to favorable learning outcomes.

The Renkl, Atkinson, and Große article, “How fading worked solution steps works: A cognitive load perspective”, reports two experiments that examined the effectiveness of using fading worked-out steps to help students’ problem solving skills in the area of probability. Successively fading out worked solution steps was expected to facilitate the transition from learning from worked-out examples in earlier stages of skill acquisition to problem solving in later stages. Experiment 1 compared students’ learning about the principles of multiplication and complementarity when the fading of each was either forward (i.e., omitting a first step) or backward (i.e., omitting a last step). Experiment 2 compared a backward fading technique with a conventional example-problem pairs technique on near and far transfer problem solving, number of errors during training, and impasse followed by self-explanation, by superficial explanations, or no explanations. Overall, the results showed that individuals learned most about those principles that were faded and fading led to fewer unproductive learning events.

The worked example effect was one of the earliest and is the most commonly studied cognitive load effect. Van Gog, Paas and Van Merriënboer indicate that the vast majority of studies have used what they term “product” based worked examples. Such worked examples demonstrate the products of solution: the problem states and the operators used to transform those states. Typically, while these problem states and operators are the ones used by experts, they leave it to the learner to infer how or why particular steps are taken. Van Gog et al. suggest that rather than using such product based worked examples, germane cognitive load might be increased by the use of “process” based examples in which each example is accompanied by a commentary or other information indicating how and why the relevant steps are taken to solve a problem. Such information can, of course, increase extraneous as well as germane cognitive load and the authors caution that split-attention and redundancy effects need to be kept in mind when using process based worked examples. Nevertheless, if designed well, process based worked examples could enhance learning and problem solving, especially transfer.

Moreno, in her paper, is concerned with discovery learning, which is one of the most popular and frequently studied instructional procedures. Indeed, it can be seen as the antecedent to major educational movements such as constructivist teaching techniques. Interestingly, despite a long history, evidence for the effectiveness of discovery learning from controlled studies is very sparse. From its inception, cognitive load theory has suggested that problem solving search imposes an extraneous cognitive load. Since discovery learning emphasizes problem solving search, there are grounds for hypothesizing that increased guidance should decrease extraneous cognitive load and increase learning. In two experiments, Moreno obtained precisely this result. Using a biology problem solving task, she found that explanatory feedback designed to provide learners with guidance increased test performance and decreased ratings of task difficulty compared to learners given corrective feedback alone.

The Brünken, Plass, and Leutner article, “Assessment of cognitive load in multimedia learning with dual-task methodology: Auditory load and modality effects”, reports two experiments in which a secondary task analysis was successfully used as a direct measure of cognitive load to provide evidence that using spoken rather than written text in conjunction with pictures or diagrams increases the cognitive load imposed on the auditory channel. In two experiments, the findings from the primary task indicated a strong modality effect with audio/visual presentations superior to visual only presentations. The secondary task indicated an increase in auditory channel cognitive load by the use of spoken rather than written text. This result can be contrasted with earlier findings by the authors (Brünken, Steinbacher, Plass and Leutner 2002) using a visually based secondary task that the visual channel is overloaded by the use of written rather than spoken text in conjunction with a (visual) diagram and that this overload is a direct cause of the modality effect. Together, the two sets of studies strongly suggest that the modality effect is caused by the transfer of load from an overloaded visual channel to a relatively underloaded auditory channel, providing an impressive result.

In CLT, learning conditions are often compared with respect not only to learning performance but also to the mental effort that was involved while learning. Several previous studies have combined performance data with the mental effort necessary for the performance whereas others studies focused on the effort during learning (2-dimensional mental efficiency measures). Although all three aspects of mental efficiency (performance, mental effort during learning and mental effort during performance testing) are important, previous studies focused on just two. In this issue, Tuovinen and Paas propose a 3-dimensional mental efficiency that integrates all three aspects. This methodological allows for a more comprehensive comparison of learning conditions. The new method was also applied in the next article by Salden et al.

For several years now, cognitive load theorists have been able to demonstrate that as learner expertise increases, the optimal instructional procedures alter. The types of tasks presented to novices should differ from those presented to more knowledgeable learners. The issue then becomes, on what basis should we choose tasks? Salden, Paas, Broers and Van Merriënboer provide a procedure for the dynamic selection of tasks based on performance, mental effort or mental efficiency. Using their procedure on an Air Traffic Control task, they found that learning times are substantially reduced for the same performance outcome when tasks are selected using any one of previous task performance, mental effort or mental efficiency. From a methodological perspective, their use of learning times in their 3-factor mental efficiency formula differs from previous efficiency measures and may well prove useful to other researchers.

This issue closes with an article by Rikers, Van Gerven, and Schmidt – "Cognitive load theory as a tool for expertise development" – discussing the contributions to this special issue and connecting cognitive load theory research to research on expertise.

The articles in this special issue demonstrate that twenty years after it was proposed, cognitive load theory is reaching maturity, both theoretically and methodologically. Our hope is that the diverse topics covered in this issue make it clear that the development and analysis of instructional methods on the basis of cognitive load theory continues to be a challenging and fruitful area of research.

References

Brünken, R., Steinbacher, S., Plass, J.L. & Leutner, D. (2002) Assessment of cognitive load within multimedia learning by the dual task methodology, *Experimental Psychology* 49: 109–119.

Chi, M., Glaser, R. & Rees, E. (1982) Expertise in problem solving. In: R. Sternberg (ed), *Advances in the Psychology of Human Intelligence*, pp. 7–75. Hillsdale, NJ: Erlbaum.

Kalyuga, S., Ayres, P., Chandler, P. & Sweller, J. (2003) The expertise reversal effect, *Educational Psychologist* 38: 23–32.

Paas, F., Renkl, A. & Sweller, J. (2003) Cognitive load theory and instructional design: Recent developments, *Educational Psychologist* 38: 1–4.

Paas, F., Tuovinen, J.E., Tabbers, H. & Van Gerven, P.W.M. (2003) Cognitive load measurement as a means to advance cognitive load theory, *Educational Psychologist* 38: 63–71.

Paas, F. & Van Merriënboer, J.J.G. (1994) Variability of worked examples and transfer of geometrical problem-solving skills: A cognitive-load approach, *Journal of Educational Psychology* 86: 122–133.

Pollock, E., Chandler, P. & Sweller, J. (2002) Assimilating complex information, *Learning and Instruction* 12: 61–86.

Renkl, A., Stark, R., Gruber, H. & Mandl, H. (1998) Learning from worked-out examples: The effects of example variability and elicited self-explanations, *Contemporary Educational Psychology* 23: 90–108.

Sweller, J. (1988) Cognitive load during problem solving, *Cognitive Science* 12: 257–285.

Sweller, J. (1999) *Instructional Design in Technical Areas*. Melbourne, Australia: ACER Press.

Teigen, K.H. (1994) Yerkes-Dodson: A law for all seasons, *Theory and Psychology* 4: 525–547.

Van Merriënboer, J.J.G. (1997) *Training Complex Cognitive Skills: A Four-Component Instructional Design Model for Technical Training*. Englewood Cliffs, NJ: Educational Technology Publications.

Van Merriënboer, J.J.G., Kirschner, P. & Kester, L. (2003) Taking the load off a learner's mind: Instructional design for complex learning, *Educational Psychologist* 38: 5–13.

Wulf, G. & Shea, C.H. (2002) Principles derived from the study of simple skills do not generalize to complex skills learning, *Psychonomic Bulletin and Review* 9: 185–211.