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# Cognitive-Load Theory: Methods to Manage Working Memory Load in the Learning of Complex Tasks

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**Abstract**
Cognitive-load researchers attempt to engineer the instructional control of cognitive load by designing methods that substitute productive for unproductive cognitive load. This article highlights proven and new methods to achieve this instructional control by focusing on the cognitive architecture used by cognitive-load theory and aspects of the learning task, the learner, and the learning environment.

**Keywords**
cognitive-load theory, working memory, instructional design, mental effort

The main goal of cognitive-load theory (CLT; Paas, Renkl, & Sweller, 2003; Sweller, Ayres, & Kalyuga, 2011; Sweller, van Merrienboer, & Paas, 1998; Sweller, van Merriënboer, & Paas, 2019) is to optimize learning of complex cognitive tasks by transforming contemporary scientific knowledge on the manner in which cognitive structures and processes are organized (i.e., cognitive architecture) into guidelines for instructional design. To achieve this goal, cognitive-load researchers attempt to engineer the instructional control of cognitive load by designing methods that substitute productive for unproductive cognitive load. The focus of this article is on methods to achieve this instructional control by focusing on the learning task, the learner, and the learning environment. To understand how these methods work, it is necessary to understand the human cognitive architecture and other main concepts used by CLT. Therefore, we begin by describing this architecture, after which we present the load-management methods that have been used by CLT researchers and describe promising methods from other research fields that are based on similar CLT principles and might be used in instructional design. The article ends with a brief discussion of the relationships among methods and an overall conclusion.

## Cognitive Architecture

The human cognitive architecture postulated by CLT has developed over several decades into a model in which the processes and structures are considered closely analogous to the processes and structures associated with evolution by natural selection (e.g., Paas & Sweller, 2012; Sweller & Sweller, 2006). Obviously, being driven by theoretical and empirical research, the cognitive architecture is continuously being developed and refined, as is evidenced, for example, by recent efforts to incorporate the physical environment (Choi, van Merriënboer, & Paas, 2014) and human movement (e.g., Sepp, Howard, Tindall-Ford, Agostinho, & Paas, 2019) as factors affecting the organization of cognitive structures and processes.

CLT uses evolutionary theory to categorize knowledge into biologically primary and secondary knowledge (Geary, 2007, 2008). Biologically primary knowledge is knowledge that we have specifically evolved to acquire over many generations, such as learning to recognize faces and listen to and speak a native language. Acquisition of this knowledge does not require explicit instruction; it is largely unconscious, effortless, rapid, and driven by intrinsic motivation. Biologically secondary knowledge, which is cultural knowledge we have not evolved to acquire, is

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best obtained with explicit instruction; it is conscious, effortful, and often needs to be driven by extrinsic motivation. Examples are learning to write, read, and perform arithmetic. CLT is concerned with the acquisition of biologically secondary knowledge and how biologically primary knowledge can be used to facilitate this. Paas and Sweller (2012) argued that biologically primary skills, such as human movement and collaboration, can be used to facilitate the learning of biologically secondary knowledge.

### *Evolutionary principles*

The cognitive architecture assumed by CLT consists of long-term memory (LTM) and working memory (WM) and is based on five basic principles (Sweller & Sweller, 2006). According to the *information-store principle*, humans are able to store very large amounts of information in LTM. According to the *borrowing-and-reorganization principle*, most of the new information stored in LTM is obtained by imitating what other people do, listening to what they say, and reading what they write. This new knowledge is reorganized by combining it with existing knowledge. When new knowledge cannot be obtained from other people, a generate-and-test procedure during problem solving can be used to acquire new knowledge, according to the *randomness-as-genesis principle*.

The processing of new information is heavily constrained because, according to the *narrow-limits-of-change principle*, novel information needs to be processed in WM prior to being stored in LTM. Contrary to LTM, WM is severely limited in both capacity (Cowan, 2001; Miller, 1956) and duration (Peterson & Peterson, 1959); people can hold from five to nine information elements for no more than 20 s, and even fewer when the information elements need to be combined, contrasted, or manipulated. The limits of WM may not be relevant when dealing with (a) biologically primary knowledge, (b) familiar information that is already well organized in cognitive schemas in LTM (e.g., for experts in a task), or (c) very simple tasks that can be performed without using schemas in LTM. But the limits of WM are especially relevant in common situations in which people are learning complex tasks that heavily deplete WM resources (Chen, Castro-Alonso, Paas, & Sweller, 2018; van Merriënboer, 1997; van Merriënboer & Kirschner, 2018).

Finally, according to the *environmental-organizing-and-linking principle*, the external environment provides a trigger to use information held in LTM to generate action appropriate to that environment. If schemas in LTM have been developed through extensive practice, they may incorporate a huge amount of information and eventually be triggered without depleting WM resources (i.e., schema automation). Cognitive schemas are used to store, organize, and reorganize knowledge by incorporating or chunking multiple elements of information into a single element with a specific function. Their incorporation in a schema means that only one element must be processed when a schema is brought from LTM to WM to govern activity. Skilled performance thus develops through the building of increasing numbers of ever more complex schemas by combining elements consisting of lower-level schemas into higher-level schemas (i.e., schema construction; Ericsson & Charness, 1994).

### *Intrinsic and extraneous load*

CLT is based on the assumption that the bottleneck for acquiring new secondary biological knowledge is the limited WM capacity (Sweller et al., 2019). To acquire new knowledge, learners have to allocate WM capacity to—that is, invest mental effort in—learning tasks. In the ideal situation, WM resources required for learning do not exceed the available resources, and all available resources can be allocated to activities that contribute to the learning process. However, in reality, there will often be high cognitive load, or even "overload," for two reasons. First, dealing with interactive information elements in complex cognitive tasks imposes a high intrinsic WM load, that is, load that is directly relevant for performing and learning the task. Second, learners also have to use WM resources for activities that are extraneous to performing and learning the task, that is, activities that are not productive for learning. Extraneous cognitive load can be caused by task-related aspects (e.g., the instructional design), by aspects of the learner (e.g., intrusive thoughts about failure), and by aspects of the learning environment (e.g., distracting information in a classroom).

According to CLT, intrinsic and extraneous cognitive load are additive (Sweller, 2010; Sweller et al., 2011). Learning tasks should be designed in such a way that the available WM capacity is efficiently used to achieve the highest return on mental effort investment. This means that extraneous load should be minimized so that WM capacity is freed, which may permit an increase in the working resources devoted to intrinsic cognitive load (also called *germane* processing).

## Exemplary Methods to Manage Cognitive Load

On the basis of the cognitive architecture, cognitive-load researchers have developed several methods to manage the learner's WM capacity. Until recently, these methods have almost exclusively targeted the learning tasks by instructional-design manipulations. However, both recent CLT research and research in fields that are not directly related to learning and education suggest that the WM capacity that is available for learning is determined not only from learning-task characteristics and available schemas in LTM (i.e., prior knowledge) but also by aspects of the learner and the physical environment. Next, we present an overview of how characteristics of the learning task, the learner, and the learning environment affect the management of WM capacity and yield important instructional consequences.

## The learning tasks

For several decades, CLT researchers have been investigating how learning-task characteristics can be used to manage learners' WM capacity and maximize learning outcomes. These studies have mainly been focused on reducing extraneous load. For a recent overview of the resulting effects, see Sweller et al. (2019). Here, we briefly describe only three of the most investigated effects, namely, the split-attention effect, the worked-example effect, and the guidance-fading effect.

***Split-attention effect.*** The split-attention effect (Pouw, Rop, De Koning, & Paas, 2019; Tarmizi & Sweller, 1988) holds that students learn more from one integrated source of information than from multiple sources of information distributed either in space (spatial split attention) or time (temporal split attention). Learning from distributed sources of information requires more attentional switching and therefore makes the mental integration process that is needed to understand the learning task more difficult than learning from integrated sources. Learning from integrated information sources imposes a lower extraneous load.

***Worked-example effect.*** This effect (Paas & Van Merriënboer, 1994; Sweller & Cooper, 1985) holds that novice students learn more from studying worked examples that provide them with a solution than from solving the equivalent problems. When learning a new task by problem solving, learners use most of their WM resources for applying the problem-solving strategy, which imposes a very high extraneous cognitive load and consequently leaves no resources for learning. In contrast, when learning through studying worked examples, all resources can be spent on learning.

***Guidance-fading effect.*** The guidance-fading effect is an example of a so-called compound effect, that is, an effect that alters the characteristics of other, simple cognitive-load effects. For novices, studying worked examples may be essential to lower cognitive load. But for more advanced learners, worked examples may become redundant and even impose an unnecessary cognitive load because they interfere with already available schemas in LTM. This general principle is important for educational programs of longer duration, in which learners gradually acquire more expertise in a task domain. It indicates that methods for novice learners need to be different from methods for more advanced learners (Renkl, 2012; van Merriënboer & Kirschner, 2018).

## The learner

Instructional design typically focuses on the design of learning tasks, but in order to manage cognitive load, it may also focus on the learner. Example methods may require or stimulate learners to collaborate on learning tasks to increase effectively available cognitive capacity, to off-load task-related information to other modalities (e.g., by gesturing), or to invest more effort in the task.

***Collaboration.*** CLT research has shown that it is possible to overcome individual WM limitations through collaboration (Kirschner, Paas, & Kirschner, 2009, 2011). It has been argued that a homogeneous group of collaborative learners can be considered as a single information-processing system consisting of multiple, limited WMs that can create a larger, more effective collective working space (Paas & Sweller, 2012). The resulting collective WM effect reflects the finding that collaborating learners can gain from each other's WM capacity during learning.

***Gesturing.*** Research suggests that gestures can support WM processing by temporarily off-loading WM resources normally devoted to internal maintenance of information, with the gesture physically maintaining the information (e.g., finger counting) and removing its demand from WM (e.g., Cook, Yip, & Goldin-Meadow, 2012; Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001; Ping & Goldin-Meadow 2010; for reviews, see Dargue, Sweller, & Jones, 2019; Risko & Gilbert, 2016). This frees up WM resources and permits them to be allocated to other relevant learning activities. In addition, gestures such as tracing can support WM processing through the physical embodiment of a process, concept, or object (Sepp et al., 2019). Once the problem to be solved is reframed in an alternate modality, WM resources are freed (e.g., Agostinho et al., 2015; Hu, Ginns, & Bobis, 2014).

***Motivational cues.*** The amount of WM resources allocated is proportional to task difficulty until the maximum level of WM resources one is willing to invest (i.e., motivation) is reached. When this upper limit is reached or when success is perceived as impossible, learners reduce their mental effort and, in some cases, even disengage from the task. Motivational cues may help learners to invest more effort. For example, Um, Plass, Hayward, and

Homer (2012) found that applying positive emotional-design principles to a multimedia learning environment (e.g., using bright, warm color combinations) increased motivation, the amount of learners' reported mental effort, and learning outcomes.

### *The learning environment*

In addition to the learning task and the learner, the environment in which tasks are performed by the learners also affects cognitive load and its management. Example methods to deal with this phenomenon may help the learner to stop monitoring irrelevant stimuli in the environment (e.g., attention-capturing stimuli reduction, eye closure) or to undertake activities that suppress cognitive states (e.g., stress, negative emotions, uncertainty) that are caused by the environment and deplete WM resources.

***Attention-capturing-stimuli reduction.*** Empirical studies have shown that environmental stimuli from the physical learning environment can impose a load on learners' WM. Noise, whether visual or auditory, can be considered as a typical irrelevant environmental stimulus that takes limited WM resources away from the learners' cognitive process. An example of such a suggestion was provided in a study by Fisher, Godwin, and Seltman (2014), who showed that while learning in science lessons, children's WM resources were consumed by unintentional monitoring of the decorated classroom environment. Children in the decorated classroom were less likely to stay focused and attained lower test scores than children in a classroom without decoration.

***Eye closure.*** Research in the field of forensic psychology has shown that eye closure reduces WM load and improves performance on eyewitness-memory tasks by freeing WM resources that would otherwise have been involved in monitoring the environment (Vredeveldt, Hitch, & Baddeley, 2011). Glenberg, Schroeder, and Robertson (1998) provided another demonstration of this phenomenon in the visual system by showing that memory retrieval could be improved when subjects averted their gaze from their environmental surroundings during cognitively difficult tasks.

***Stress-suppressing activities.*** In stressful situations, such as high-stakes exams, WM resources are consumed by intrusive worries about failure, especially in highly anxious students. A study conducted by Ramirez and Beilock (2011) showed that a brief expressive writing assignment that occurred immediately before a test improved test performance by freeing WM resources associated with worries about failure.

## Discussion

In this article, we have shown how characteristics of the learning task, the learner, and the learning environment can be used in instructional-design decisions to manage the learner's WM resources. It is important to note that these characteristics interact and should always be considered by instructional designers as one system in which manipulating one aspect has consequences for the whole system. For example, implementing motivational cues to increase the willingness of learners to allocate WM resources to the learning task may work only when that learning task is not associated with a high intrinsic cognitive load (e.g., when the task is very difficult for the learners) or when the environment does not include irrelevant stimuli that are monitored by the learner and thus create a high extraneous cognitive load.

Whereas some of the described methods have been investigated extensively and can easily be used by instructional designers, some methods have been identified outside the field of learning and education and need to be investigated systematically before instructional guidelines can be formulated. We hope that the categorization of methods presented in this article will encourage researchers to start investigating this.

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Sepp, S., Howard, S., Tindall-Ford, S., Agostinho, S., & Paas, F. (2019). (See References). Presentation of an integrated model of working memory accounting for recent findings of research regarding the human motor system.

Sweller, J., van Merriënboer, J. J. G., & Paas, F. (2019). (See References). Summary of the last 20 years of cognitive-load theory and sketch of directions for future research.

### Transparency

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