Cognitive Load Theory Applied to Multimedia Learning Environments

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The online learning industry continues to grow along with an increase in the use of multimedia learning applications. Multimedia, when adequately designed, can provide an effective platform for learning. However, multimedia instruction can also be poorly designed, leading to confusion and mental overload on the part of the learner. Understanding cognitive load and its effects on learning can help instructional designers produce effective multimedia applications. This paper describes the cognitive load theory and its primary components, explains several types of cognitive load effects, and presents a set of commonly accepted multimedia design principles that originated from cognitive load theory.

Cognitive Load Theory

Cognitive load theory was "explicitly developed as theory of instructional design based on our knowledge of human cognitive architecture" (Sweller, Ayres, & Kalyuga, 2011, p. v). Developed by John Sweller in the late 1980s, cognitive load theory used the understanding of human cognition as the framework for developing instructional design principles, many of which apply to online, multimedia learning environments. Cognitive load theory is straightforward in concept, yet comprehensive in scope. To apply cognitive load theory to instructional design, it is important to understand basic concepts of human cognitive architecture and cognitive load.

Human Cognitive Architecture

Human cognitive architecture is the "manner in which human cognitive structures are organized" (Sweller et al., 2011, p. v). This architectural model explains how humans think, learn, and solve problems. Grounded in the theory of evolution and natural selection, human cognitive architecture defines two categories of information. *Biologically primary knowledge* is instinctual knowledge that humans have evolved to acquire. *Biologically secondary knowledge* is information that humans have needed to survive culturally but did not learn during the process of evolution. This latter category is what educational institutions were designed to facilitate. Understanding human cognitive architecture is the first step in understanding how biologically secondary information is acquired. Human cognitive architecture includes three basic components—working memory, long-term memory, and informational schemas.

Working memory. *Working memory* is the conscious part of the human mind. Working memory is limited in its capacity and can only hold about seven elements of information at a time (Miller, 1956). Sweller, van Merrienboer, and Paas (1998) explain that when a human organizes, compares, or contrasts information, they are processing the information in working memory. Only two or three such elements of information can be held in working memory while processing other information. Working memory is used for any conscious activity, such as when learners are using a multimedia application to learn. When a learner attempts to process too many elements of information at once, working memory can become overwhelmed. The purpose of the cognitive load theory is to provide instructional design principles that ensure the working memory of learning individuals does not become overwhelmed.

Long-term memory. Humans are not aware of their *long-term memory.* Sweller et al. (1998) explain that humans are aware of the contents of long-term memory only after it has been filtered through working memory. Long-term memory stores information that humans have practiced, or have been exposed to repeatedly, over a period of time. There appears to be an unlimited amount of information that can be stored in long-term memory. *Novel information* is new information that has not yet been stored in long-term memory. It is processed in working memory, and then stored in long-term memory. Once stored, the information becomes available for use by the working memory as new information is processed.

Schema construction. Information is stored in long-term memory in the form of *schemas.* "Schemas organize information in categories that are related in systematic and predictable ways" (Driscoll, n.d., p. 38). Schemas are constructed by processing information in working memory, and then storing the processed information in long-term memory. For example, when a person learns about a farm, they create a schema in their long-term memory that holds information about farms. As they learn more about farms, the farm schema is pulled into working memory as a single informational element, and the new information is added to the farm schema. The updated farm schema is then stored again in long-term memory. This example shows how schemas as single elements in working memory help to reduce the amount of information being processed.

Schema automation. Information is processed either consciously or automatically. Working memory is always used when processing information consciously. However, working memory is by-passed when processing information automatically. For example, when learning how to drive a car, a person uses their working memory to learn about all the various aspects of starting, driving, turning, and parking the car. After much practice, these activities take very little conscious effort because the schemas used to store the information in long-term memory have become *automatic*. "Automated schemas both allow fluid performance on familiar aspects of tasks and—by freeing working memory capacity—permit levels of performance on unfamiliar aspects that otherwise might be quite impossible" (Sweller et al., 1998, p. 258).

Cognitive Load

The primary goal of instruction is "the construction and the automation of schemas that are useful for solving the problems of interest" (Sweller et al., 1998, p. 258). To construct and use schemas, information must be processed in working memory, which can be overwhelmed by trying to process too many informational elements at the same time. Cognitive load theory uses our knowledge of human cognitive architecture to develop instructional design principles that will reduce the cognitive workload of working memory. There are three types of cognitive load.

Intrinsic cognitive load. The interaction between the level of difficulty regarding the instructional material and the learner's expertise is called *intrinsic cognitive load.* This type of cognitive load "primarily depends on the number of elements that must be simultaneously processed in working memory, which, in turn, depends on the extent of element interactivity of the material or task that must be learned" (van Merrienboar & Ayres, 2005, p. 6). For example, a learner may have difficulty learning a new subject. Breaking the subject up into several small topics may help to reduce the learner's cognitive load.

Extraneous cognitive load. Information elements that are not relevant to the learning experience but require the learner to use working memory cause *extraneous cognitive load*. Van Merrienboar and Ayers (2005) explain that this type of cognitive load can be corrected by improving the instructional design elements. For example, if a graph is presented as part of the instruction, but it is not needed, it will cause extraneous cognitive load on the part of the learner and should be removed.

Germane cognitive load. "*Germane cognitive load* is associated with processes that are directly relevant to learning, such as schema construction and automation" (van Merrienboar & Ayres, 2005, p. 7). Germane cognitive load processes, constructs, and automates schema in long-term memory. Germane cognitive load must be maximized to promote deep learning experiences.

Total cognitive load. The three types of cognitive load require a delicate balance with each other in order to create effective learning situations. The sum of intrinsic, extraneous, and germane cognitive loads equals the *total cognitive load* a person can handle. The primary instructional principle offered by cognitive load theory is to "increase germane cognitive load, within the limits of totally available processing capacity" (van Merrienboar & Ayres, 2005, p. 8). This requires extraneous cognitive load to be reduced as much as possible while managing the intrinsic cognitive load.

Cognitive load and instructional design. Sweller et al. (1998) argue that "the cognitive load imposed by instructional designs should be the pre-eminent consideration when determining design structures" (p. 262). Analyzing instructional designs using the cognitive load perspective results in effective learning programs. Inadequate instructional designs do not incorporate cognitive load concepts into the design. Instructional material that is high in interactivity, such as multimedia learning applications, need to consider the cognitive load of learners because working memory will be reduced when the students attempt to learn both the instructional material and the instructional program. It is vital in these situations to reduce extraneous cognitive load and focus on directing learner attention to the processes that are required for constructing schemas in long-term memory.

Cognitive Load Effects and Instructional Procedures

Cognitive load creates both positive and negative effects for learners. Cognitive load theory was designed to improve instruction by providing procedures that attempt to reduce negative effects. Cognitive load theory has evolved over the past three decades as a direct result of the effects that are encountered during research and practical application. As new instructional procedures are developed and used or tested, the failures encountered result in the theory being improved and new instructional effects being defined. "Ultimately, the theory stands or falls according to its ability to generate novel, useful, instructional procedures" (Sweller et al., 2011,

p. viii). There are numerous cognitive load effects that have been identified through research. A few of these effects are discussed below.

Modality effect. The *modality effect* is associated with multimedia applications that contain visual elements such as text and graphics as well as auditory elements such as narration. Reinwein (2011) explains how visual and audio elements are processed separately in different subsystems of working memory. Each subsystem has a limited processing capability and the processing that takes place in each subsystem cannot be easily exchanged for the other. For example, pictures and text are processed in the visual subsystem, which can lead to a cognitive overload if the two different types of information are processed at the same time. On the other hand, narration and graphics are processed using both subsystems of working memory, which is less likely to overload cognitive processes.

Split attention effect. *Split attention* occurs when learners must divide their focus between at least two sources of information that are each essential to understanding the other and are located in different places or provided at different times in the instructional material. For example, some information about a concept is provided as text and the rest of the information is provided in a chart. Clarke, Ayres, and Sweller (2005) explain how this effect forces the learner to integrate two different sources of information in their mind, which interferes with the learner's ability to construct and automate a schema. The instructional designer can easily correct this effect by integrating all necessary information in one location.

Redundancy effect. Presenting the same information in a different manner creates the *redundancy effect*. Although it may seem that redundancy should reduce cognitive load, redundancy actually increases cognitive load because working memory is spent processing unnecessary, repeated information. Schnotz and Rasch (2005) studied the cognitive load effects of animation in multimedia learning applications. Their study compared manipulation pictures against simulation pictures with text. *Manipulation pictures* are animations that require more interaction and control on the part of learners than *simulation pictures*, which are animations that require less intervention. They concluded that animation in multimedia applications produces mixed results. While beneficial in some circumstances, animations with text can produce additional cognitive load because the multimedia program includes redundant information.

Interactivity effect. The nature of instructional multimedia applications requires learners to interact with the program. Such interactivity is believed to be vital to the acquisition of knowledge and cognitive skill development and contributes to higher engagement on the part of the learner and thus deeper learning opportunities. “From a cognitive perspective, the utility of incorporating interactivity in computer-based systems is that it allows the learner to influence the flow of information in terms of timing or content” (Evans & Gibbons, 2007, p. 1148). Moreno and Meyer (2007) identify five types of interactivity. *Dialoguing* occurs when the application and learner exchange information, such as when the learner receives feedback from performing an action. *Controlling* is the means by which learners control the order and pace of the presentation provided by the application. *Manipulating* is when the learner sets display preferences, moves elements around on the visual display, or changes the image size by zooming in or out. *Searching* is the process of finding information by performing queries or selecting options. Finally, *navigating* is the process of moving around the application. Effective multimedia learning applications include all five types of interactivity.

Expertise reversal effect. Novice learners require more elementary information than learners who are more knowledgeable. This can cause the *expertise reversal effect*, where more experienced learners find basic information they already understand to be redundant and tend to ignore it. For example, Clarke et al. (2005) performed an experiment that used spreadsheet software to help students learn math. Students with a low level of spreadsheet knowledge were taught how to use the spreadsheets, and then received instruction on how to use the spreadsheets to learn math. Those results were compared to students with a greater level of spreadsheet knowledge that were provided with spreadsheet and math instruction at the same time. The results were consistent with the expertise reversal effect and showed that the technology should be learned before being presented with instructional material about a subject to learn. This is especially important with e-learning applications. "Students should not be required to use e-learning programs until they are thoroughly familiar with them. Only at that point, should discipline material be introduced" (Clarke et al., 2005, p. 23).

Learner motivation effects. Paas, Tuovinen, van Merrienboer, and Darabi (2005) discovered a cognitive load effect not previously identified. *Learner motivation effect* occurs as a result of the relative efficiency of instructional material. Efficiency is considered high if resulting performance is high and is achieved with a low amount of mental effort. Low efficiency is associated with a large amount of mental effort and low performance. Paas et al. argued that efficiency needed to be coupled with motivation in order to show high achievement. Their study focused on the relation between performance and mental effort and recommended that motivational perspectives should be included in instructional design formats.

Multimedia Design Principles

The "aim of instructional design is to facilitate the acquisition of knowledge in long-term memory via a working memory that is limited in capacity and duration until it is transformed by knowledge held in long-term memory" (Sweller et al., 2011, p. vii). Ultimately, the point of understanding cognitive load theory is to design effective instructional material. The following information describes common cognitive overload situations encountered with multimedia applications and suggestions for correcting these overload situations. A set of commonly used multimedia principles is also discussed.

Overcoming Cognitive Overload in Multimedia Applications

Mayer and Moreno (2003) discuss the concept of *dual-channels* where the auditory/verbal channel within working memory is used to process auditory and verbal input and the visual/pictorial channel is used to process visual and pictorial input. This is the same concept as the modality effect previously described. Mayer and Moreno then examine *cognitive overload,* a situation where the learner's cognitive processing is greater than their available cognitive capacity. They identified five overload scenarios and recommended nine solutions for reducing cognitive load in multimedia learning applications.

One channel is overloaded with essential processing demands. In this scenario, a learner experiences cognitive overload in one learning channel due to a split-attention effect. For example, an animation on one part of the screen describes part of a concept and text at the bottom of the screen describes the remainder of the concept. Mayer and Moreno (2003) recommend offloading some of the information to a different channel. Using the example above, this would mean replacing the text at the bottom of the screen with narration. This way, the auditory/verbal channel is listening to the text while the visual/pictorial channel is watching the animation, thus reducing cognitive overload.

Both channels are overloaded with essential processing demands. This scenario describes how a learner can experience cognitive overload when both channels are overloaded. For example, if the learner is expected to watch a narrated animation about a topic that was previously presented as text in a fast-paced presentation, the learner may not have enough time to process all the information through both channels. Mayer and Moreno (2003) recommend segmenting the multimedia presentation so there is more time to process information previously learned on one channel before being exposed to it again on a different channel. An alternative solution would be to provide pre-training to learners so they have the opportunity to digest prerequisite information.

One or both channels are overloaded by combination of essential and incidental processing demands. In this scenario, the learner is presented with both essential information about the subject and information that may be related, but is not pertinent to the learning task. For example, a musical background or links to video clips that are not directly related to the learning material may cause a cognitive overload. Mayer and Moreno (2003) recommend removing any non-essential information from the presentation that could take the learner's mind off the essential subject matter. If removing the extraneous information is not possible, an alternative solution would be to provide clues, or *signals*, on how to select or organize the material presented. This can be accomplished by using color to highlight essential information, organizing information from essential to extraneous by use of headings, or using graphic maps to show different parts of the lesson material and their relative importance.

One of both channels are overloaded by the combination of essential and incidental processing demands. In this scenario, not only is the material overloading the learner by presenting incidental material with essential information, but the essential information is also presented in a manner that confuses the learner. For example, graphics are placed at the top of the screen and corresponding text is placed at the bottom, intermixed with incidental information. Mayer and Moreno (2003) suggest aligning words and pictures in such a way that they are placed closely together to correct this situation. This way, learners can look at a picture and immediately see the corresponding text. Essential information should be presented first, and incidental information should be placed at the bottom of the page. An alternate solution would be to eliminate any redundancy that might exist. For example, if the page provides simultaneously displayed text, animation, and narration, eliminate one of the redundancies so that one instance uses the audio/verbal channel and the other instance uses the visual/pictorial channel.

One of both channels are overloaded by the combination of essential processing and representational holding. In this last scenario, the learner experiences cognitive overload due to attempting to engage in essential processing of information as well as representational holding. *Representational holding* is when the "cognitive process aimed at holding a mental representation in working memory during the meaning-making process" (Moreno & Mayer, 2007, p. 314). For example, an illustration appears on one page and the explanation of the illustration appears on the next page. The learner is expected to remember, or representationally hold, the image in working memory on one channel while trying to process the new information on a separate page using the other channel. Mayer and Moreno (2003) suggest synchronizing visual and auditory material so that it appears on the same page, in close proximity to each other.

Common Multimedia Design Principles

In their later work, Moreno and Mayer (2007) present several cognitive design principles for multimedia learning applications. Moreno and Mayer base these principles on the result of extensive research and empirical support.

Guided activity principle. According to this principle, students are able to learn more efficiently when there is a *pedagogical agent* that helps to guide them through the learning process. In multimedia instruction, a pedagogical agent is often depicted as a character who plays the role of a tutor or guide. The agent helps to guide the student through their own discovery.

Such guidance helps students to select, organize, and integrate new information, thus reducing cognitive load.

Reflection principle. Effective learning depends on providing opportunities for students to reflect upon their actions and what they have learned. An example of how to implement this would be to ask students to explain what they learned after answering a quiz question correctly. This enables students to process information mindfully, thus helping them to create information schemas more effectively.

Feedback principle. The effectiveness of a multimedia learning application is dependent upon the "relationship between the quality of feedback given by the system and the student's prior knowledge" (Moreno & Mayer, 2007, p. 318). The type of feedback depends on the student's knowledge level. For example, learners with low-levels of knowledge may require explanatory feedback whereas more knowledgeable learners may only require corrective feedback. *Explanatory feedback* provides explanations of concepts tested and is effective when incorrect answers are based on lack of knowledge or misconceptions. *Corrective feedback* lets the learner know whether or not they answered the question correctly and may provide the correct answer without lengthy explanation. Quality feedback reduces extraneous processing and thus reduces cognitive load.

Pacing principle. Students learn more efficiently when they are allowed to control the pace of the multimedia presentation. For example, a Continue button that the learner can click allows the learner to progress through the presentation at their own pace as opposed to a presentation that automatically displays the next page after a specific period of time has elapsed. By allowing learners to control the pace, representational holding which leads to cognitive overload is reduced.

Pretraining principle. Students tend to learn more efficiently when they receive relevant training before starting the multimedia learning application. Such training helps learners to store schemas of information in long-term memory that can be used in working memory while using the learning application, thus reducing cognitive load.

Conclusion

The increase in multimedia learning applications requires the use of instructional principles that are designed to foster effective learning. The cognitive load theory offers substantial scientific knowledge and empirical evidence to support its use in the design of multimedia programs. Understanding human cognitive architecture helps an instructional designer understand how the human mind works. Applying this knowledge to an understanding of the various types of cognitive load can help an instructional designer focus on developing applications that minimize cognitive overload. Realizing the various positive and negative effects of cognitive load can help an instructional designer tailor a program to avoid specific situations where cognitive load would interfere with a student's ability to learn. And, finally, understanding the basic design principles that rose from cognitive design theory will help an instructional designer develop multimedia applications that use graphics, text, and sound in the most effective way possible. Thus, cognitive load theory is a practical learning theory for developing effective multimedia learning applications.

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