Cognitive Load: Mastering Your Brain’s Limited Bandwidth

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In cognitive psychology, cognitive load refers to the total amount of mental effort being used in the working memory. Cognitive load theory was developed out of the study of problem solving by John Sweller in the late 1980s. Sweller argued that instructional design can be used to reduce cognitive load in learners. Cognitive load theory differentiates cognitive load into three types: intrinsic, extraneous, and germane.

Intrinsic cognitive load is the effort associated with a specific topic. Extraneous cognitive load refers to the way information or tasks are presented to a learner. And, germane cognitive load refers to the work put into creating a permanent store of knowledge, or a schema.

Researchers Paas and Van Merriënboer developed a way to measure perceived mental effort which is indicative of cognitive load. Task-invoked pupillary response is a reliable and sensitive measurement of cognitive load that is directly related to working memory. Measuring humans' pupil responses has the potential to improve human-computer interaction and adaptive decision support systems. Heavy cognitive load can have negative effects on task completion, and it is important to note that the experience of cognitive load is not the same in everyone. The elderly, students, and children experience different, and more often higher, amounts of cognitive load.

High cognitive load in the elderly has been shown to affect their center of balance. With increased distractions and cell phone use students are more prone to experiencing high cognitive load which can reduce academic success. Children have less general knowledge than adults which increases their cognitive load. Recent theoretical advances include the incorporation of embodied cognition in order to predict the cognitive load resulting from embodied interactions.

Theory

Cognitive load theory has been designed to provide guidelines intended to assist in the presentation of information in a manner that encourages learner activities that optimize intellectual performance". Sweller's theory employs aspects of information processing theory to emphasize the inherent limitations of concurrent working memory load on learning during instruction. It makes use of the schema as primary unit of analysis for the design of instructional materials.

History

The history of cognitive load theory can be traced to the beginning of Cognitive Science in the 1950s and the work of G.A. Miller. In his classic paper, Miller was perhaps the first to suggest our working memory capacity has inherent limits. His experimental results suggested that humans are generally able to hold only seven plus or minus two units of information in short-term memory. And in the early 1970s Simon and Chase were the first to use the term "chunk" to describe how people might organize information in short-term memory. This chunking of memory components has also been described as schema construction.

In the late 1980s John Sweller developed cognitive load theory (CLT) while studying problem solving. Studying learners as they solved problems, he and his associates found that learners often use a problem solving strategy called means-ends analysis. He suggests problem solving by means-ends analysis requires a relatively large amount of cognitive processing capacity, which may not be devoted to schema construction. Sweller suggests that instructional designers should prevent this unnecessary cognitive load by designing instructional materials which do not involve problem solving. Examples of alternative instructional materials include what are known as worked-examples and goal-free problems.
In the 1990s, cognitive load theory was applied in several contexts. The empirical results from these studies led to the demonstration of several learning effects: the completion-problem effect; modality effect; split-attention effect; worked-example effect; and expertise reversal effect.

Types

Cognitive load theory provides a general framework and has broad implications for instructional design, by allowing instructional designers to control the conditions of learning within an environment or, more generally, within most instructional materials. Specifically, it provides empirically-based guidelines that help instructional designers decrease extraneous cognitive load during learning and thus refocus the learner's attention toward germane materials, thereby increasing germane (schema related) cognitive load. This theory differentiates between three types of cognitive load: intrinsic cognitive load, germane cognitive load, and extraneous cognitive load.

Intrinsic

Intrinsic cognitive load is the inherent level of difficulty associated with a specific instructional topic. The term was first used in the early 1990s by Chandler and Sweller. According to them, all instruction has an inherent difficulty associated with it (e.g., the calculation of 2 + 2, versus solving a differential equation). This inherent difficulty may not be altered by an instructor. However, many schemas may be broken into individual "subschemas" and taught in isolation, to be later brought back together and described as a combined whole.

Extraneous

Extraneous cognitive load is generated by the manner in which information is presented to learners and is under the control of instructional designers. This load can be attributed to the design of the instructional materials. Because there is a single, limited cognitive resource, using resources to process the extraneous load reduces the amount of resources available to process the intrinsic load and germane load (i.e., learning). Thus, especially when intrinsic and/or germane load is high (i.e., when a problem is difficult), materials should be designed so as to reduce the extraneous load.

An example of extraneous cognitive load occurs when there are two possible ways to describe a square to a student. A square is a figure and should be described using a figural medium. Certainly an instructor can describe a square in a verbal medium, but it takes just a second and far less effort to see what the instructor is talking about when a learner is shown a square, rather than having one described verbally. In this instance, the efficiency of the visual medium is preferred. This is because it does not unduly load the learner with unnecessary information. This unnecessary cognitive load is described as extraneous.

Chandler and Sweller introduced the concept of extraneous cognitive load. This article was written to report the results of six experiments that they conducted to investigate this working memory load. Many of these experiments involved materials demonstrating the split attention effect. They found that the format of instructional materials either promoted or limited learning. They proposed that differences in performance were due to higher levels of the cognitive load imposed by the format of instruction. "Extraneous cognitive load" is a term for this unnecessary (artificially induced) cognitive load.

Germane

Germane cognitive load is that load devoted to the processing, construction and automation of schemas. It was first described by Sweller, Van Merriënboer and Paas in 1998. While intrinsic cognitive load is generally thought to be immutable (although techniques can be applied to manage complexity by segmenting and sequencing complex material), instructional designers can manipulate extraneous and germane load. It is suggested that they limit extraneous load and promote germane load.

Until the 1998 article by Sweller, Van Merriënboer & Paas, cognitive load theory primarily concentrated on the reduction of extraneous cognitive load. With this article, cognitive load researchers began to seek ways of redesigning instruction to redirect what would be extraneous load, to now be focused toward schema construction (germane load). Thus it is very important for instructional designers to "reduce extraneous cognitive load and redirect learners' attention to cognitive processes that are directly relevant to the construction of schemas".

Measurement

Paas and Van Merriënboer developed a construct (known as relative condition efficiency) which helps researchers measure perceived mental effort, an index of cognitive load. This construct provides a relatively simple means of comparing instructional conditions. It combines mental effort ratings with performance scores. Group mean z-scores are graphed and may be compared with a one-way Analysis of variance (ANOVA).

Paas and Van Merriënboer used relative condition efficiency to compare three instructional conditions (worked examples, completion problems, and discovery practice). They found learners who studied worked examples were the most efficient, followed by those who used the problem completion strategy. Since this early study many other researchers have used this and other constructs to measure cognitive load as it relates to learning and instruction.

The ergonomic approach seeks a quantitative neurophysiological expression of cognitive load which can be measured using common instruments, for example using the heart rate-blood pressure product (RPP) as a measure of both cognitive and physical occupational workload. They believe that it may be possible to use RPP measures to set limits on workloads and for establishing work allowance.

Task-invoked pupillary response is a form of measurement that directly reflects the cognitive load on working memory. Greater pupil dilation is found to be associated with high cognitive load. Pupil constriction occurs when there is low cognitive load. Task-invoked pupillary response shows a direct correlation with working memory, making it an effective measurement of cognitive load explicitly unrelated to learning.

Some researchers have compared different measures of cognitive load. For example, Deleeuw and Mayer (2008) compared three commonly used measures of cognitive load and found that they responded in different ways to extraneous, intrinsic, and germane load.

Established eye movement and pupillary response indicators of cognitive load are:

pupillary diameter mean
pupillary diameter deviation
number of gaze fixations > 500 milliseconds
saccad speed
pupillary hippus

Individual Differences in Processing Capacity

Evidence has been found that individuals systematically differ in their processing capacity. For example, there are individual differences in processing capacities between novices and experts. Experts have more knowledge or experience with regard to a specific task which reduces the cognitive load associated with the task. Novices do not have this experience or knowledge and thus have heavier cognitive load.

It has been theorized that an impoverished environment can contribute to cognitive load. Regardless of the task at hand, or the processes used in solving the task, people who experience poverty also experience higher cognitive load. A number of factors contribute to the cognitive load in people with lower socioeconomic status that are not present in middle and upper-class people.
Identifying the processing capacity of individuals could be extremely useful in further adapting instruction (or predicting the behavior) of individuals. Accordingly, further research would clearly be desirable. First, it is essential to compute the memory load imposed by detailed analysis of the processes to be used. Second, it is essential to ensure that individual subjects are actually using those processes. The latter requires intensive pre-training.

Effects of Heavy Cognitive Load

A heavy cognitive load typically creates error or some kind of interference in the task at hand. A heavy cognitive load can also increase stereotyping. Stereotyping is an extension of the Fundamental Attribution Error which also increases in frequency with heavier cognitive load. The notions of cognitive load and arousal contribute to the "Overload Hypothesis" explanation of social facilitation: in the presence of an audience, subjects tend to perform worse in subjectively complex tasks (whereas they tend to excel in subjectively easy tasks).

Elderly

The danger of heavy cognitive load is seen in the elderly population. Aging can cause declines in the efficiency of working memory which can contribute to higher cognitive load. The relationship between heavy cognitive load and control of center of mass are heavily correlated in the elderly population. As cognitive load increases, the sway in center of mass in elderly individuals increases. Another study examined the relationship between body sway and cognitive function and their relationship during multitasking and found disturbances in balance led to a decrease in performance on the cognitive task Heavy cognitive load can disturb balance in elderly people. Conversely, an increasing demand for balance can increase cognitive load.

College Students

With the widespread acceptance of laptops in the classroom an increasing cognitive load while in school is a major concern. With the use of Facebook and other social forms of communication, adding multiple tasks is hurting students performance in the classroom. When many cognitive resources are available, the probability of switching from one task to another is high and does not lead to optimal switching behavior. Both students who were heavy Facebook users and students who sat nearby those who were heavy Facebook users performed poorly and resulted in lower GPA.

Children

The components of working memory as proposed by British psychologists, Alan Baddeley and Graham Hitch, are in place at 6 years of age. However, there is a clear difference between adult and child knowledge. These differences are due to developmental increases in processing efficiency. Children lack general knowledge, and this is what creates increased cognitive load in children. Children in impoverished families often experience even higher cognitive load in learning environments than those in middle-class families. These children do not hear, talk, or learn about schooling concepts because their parents often do not have formal education. When it comes to learning, their lack of experience with numbers, words, and concepts increases their cognitive load.

As children grow older they develop superior basic processes and capacities. They also develop metacognition, which helps them to understand their own cognitive activities. Lastly, they gain greater content knowledge through their experiences. These elements help reduce cognitive load in children as they develop.

Gesturing is a technique children use to reduce cognitive load while speaking. By gesturing, they can free up working memory for other tasks. Pointing allows a child to use the object they are pointing at as the best representation of it, which means they do not have to hold this representation in their working memory, thereby reducing their cognitive load. Additionally, gesturing about an object that is absent reduces the difficulty of having to picture it in their mind.

Embodiment and Interactivity

Cognitive load theorists have asked for updates that makes CLT more compatible with insights from embodied cognition research. As a result, Embodied Cognitive Load Theory has been suggested as a means to predict the usefulness of interactive features in learning environments. In this framework, the benefits of an interactive feature (such as easier cognitive processing) need to exceed its cognitive costs (such as motor coordination) in order for an embodied mode of interaction to increase learning outcomes.

Computational Representation of Mental Workload

Human mental workload has gained importance, in the last few decades, as a design concept in human-computer interaction. At a low level, while processing information, often people feel annoyed and frustrated; at higher level, mental workload is critical and dangerous as it leads to confusion, it decreases the performance of information processing and it increases the chances of errors and mistakes.

At an early system design phase, designers require some explicit model to predict the mental workload imposed by their technologies on end-users so that alternative system designs can be evaluated. However, human mental workload is a multifaceted and complex construct mainly applied in cognitive sciences. A plethora of ad-hoc definitions can be found in the literature. Generally, it is not an elementary property, rather it emerges from the interaction between the requirements of a task, the circumstances under which it is performed and the skills, behaviours and perceptions of the operator. Although measuring mental workload has advantages in interaction and interface design, its formalisation as an operational and computational construct has not sufficiently been addressed. Many researchers agree that too many ad-hoc models are present in the literature and that they are applied subjectively by mental workload designers thereby limiting their application in different contexts and making comparison across different models difficult.

In a recent work, the nature of the concept of mental workload, from a computational perspective, is argued to be a defeasible phenomenon. It is a concept built upon a set of reasons that can be defeated by additional reasons. The reasonable assumptions behind this are:

Assumption 1: human mental workload is a complex construct built over a network of pieces of evidence;
Assumption 2: accounting and understanding the relationships of accounted pieces of evidence as well as resolving the inconsistencies that might arise from their interaction is essential in modelling human mental workload.

The main contribution of this thesis is the introduction of a methodology, developed as a formal modular framework, to represent mental workload as a defeasible computational concept and to assess it as a numerical usable index. The research contributes to the body of knowledge by providing a modular framework built upon defeasible reasoning and formalised using argumentation theory in which workload can be measured, analysed, explained and applied in different contexts. The framework follows the Popperian test of falsifiability, this being also flexible and replicable. The preliminary solution proposed was designed for those scholars interested in engaging in the multi-disciplinary domain of mental workload and it is aimed at increasing its understanding and use. A further goal is to offer a new perspective on the formalisation of mental workload, encouraging further research on its representation, assessment and application in more general fields such as human-computer interaction, education, and educational psychology.