CHAPTER 2

Implications of Cognitive Load Theory for Multimedia Learning

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Abstract

Humans have evolved with a working memory that has no logical central executive available when required to organise novel information. Consequently, failing instruction, we must randomly propose organisational combinations and test them for effectiveness. This procedure is only possible with a very limited number of elements and as a consequence, working memory is severely limited when dealing with novel information. In contrast, familiar, organised information previously stored in long-term memory can act as a central executive and eliminate the need for working memory limitations. These structures are central to cognitive load theory. They suggest that instruction should act as substitute for the missing central executive when dealing with novel information and that factor, in turn, determines multimedia instructional principles.

Introduction

Good instructional design is driven by our knowledge of human cognitive structures and the manner in which those structures are organised into a cognitive architecture. Without knowledge of relevant aspects of human cognitive architecture such as the characteristics of and intricate relations between working memory and long-term memory, the effectiveness of instructional design is likely to be random. Cognitive load theory has been one of the theories used to integrate our knowledge of human cognitive structures and instructional design principles. This chapter is concerned with the elements of that theory and its general implications for multimedia learning, specifically, words presented in spoken or written form along with pictures or diagrams.

I will begin with some aspects of human cognitive architecture relevant to instruction. Along the way I will suggest that the processes and structures of human cognition are closely analogous to the processes and structures associated with evolution by natural selection and that accordingly, evolutionary theory, which is much older and better developed than cognitive theory, can be used as a guide to assess which instructional procedures may or may not be effective.

Long-Term Memory

Long-term memory has the same central role in human cognition as a genetic code has in biology (Sweller, 2003). Just as a genetic code heavily determines a biological life, so long-term memory heavily determines our cognitive lives. All the information in a genetic code has been determined by adaptation to an environment (evolution by natural selection) and similarly, everything in long-term memory has been learned in order to cognitively adapt to an environment. On this analogy between a genetic code and long-term memory, almost all human cognitive activity is determined by information held in long-term memory. This information must be learned over time just as the information held in a genetic code is acquired over time. Learning is defined as an alteration in long-term memory. If nothing has altered in long-term memory nothing has been learned. Accordingly, appropriate alterations to long-term memory should be the primary aim of instruction.

The suggestion that information in long-term memory is analogous to a genetic code, that most human cognitive activity is driven by information held in long-term memory, and that the aim of instruction should be to alter long-term memory, imply that the long-term memory store is very large. The evidence for a very large long-term memory is now overwhelming. The origin of this discovery is unusual: the game of chess.

De Groot (1965) studied the factors that permitted chess grand masters to almost invariably defeat less able players. The only factor he could find that distinguished between more able and less able chess players was in memory for board configurations taken from real games. If shown a board configuration taken from a real game for a few seconds and then asked to reproduce that configuration, chess grand masters could replace most of the pieces correctly. Less able players could correctly replace few of the pieces. Chase and Simon (1973) replicated this result but found it could not be replicated using random board configurations. The result only was obtainable using board configurations taken from real games.

In the late 1970s and 1980s, a similar result was obtained many times in a variety of fields by several investigators (e.g., Egan & Schwartz, 1979; Jeffries, Turner, Polson, & Atwood, 1981; Sweller & Cooper, 1985). Experts have a vastly superior memory to novices for problem states in their field of expertise. For example, Simon and Gilmartin (1973) have estimated that chess grand masters have memorised up to 100,000 board configurations. It is this store of information in long-term memory that constitutes expertise. As a consequence, problem-solving skill is critically determined by information in long-term memory concerning problem states and the best move associated with each state. Such knowledge held in long-term memory allows an expert to immediately recognise most of the situations faced and the actions required by that situation. That large body of knowledge permits the fluency shown by experts in their own area. A major function of instructional design is to assist learners to acquire a similar fluency. Fluent procedures imply that the necessary knowledge that underpins skilled performance in any substantive area has been acquired.

The Structure of Knowledge in Long-Term Memory

Emphasising the importance of accumulating knowledge in long-term memory as the primary goal of instruction is sometimes misinterpreted as an emphasis on rote learning. In fact, both rote learning and learning with understanding result in changes in long-term memory. Rote learning occurs when some connections between elements occur but other, essential connections, are omitted. If a student learns to recite the letters of the alphabet but not how they can be used to produce written language, or learns to recite a multiplication table but not that multiplication is a shorthand procedure for repeated addition, there are changes in long-term memory due to the rote learned material. If the student begins to learn to read or learns to use multiplication instead of repeated addition to determine the cost of three pencils, as well as the changes in long-term memory due to rote learning, there are further changes due to the increased level of understanding. Understanding can be largely described by the additional changes in long-term memory (along with the effect of those changes on working memory to be discussed in the following text). Without changes in long-term memory, nothing has been understood.

What is the nature of changes in long-term memory as material is learned? The process probably can best be described in terms of schema construction. Schemas are cognitive constructs that allow multiple elements of information to be categorised as a single element. (For examples and theory associated with problem-solving schemas, see Chi, Glaser, & Rees, 1982; Larkin, McDermott, Simon, & Simon, 1980.) An intuitive feel for the power of schemas and indeed, an intuitive feel for the power of information held in long-term memory, may be gleaned by considering the cognitive processes required to read this page. Objectively, writing is an almost indescribably complex series of squiggles. A person can read because schemas for individual letters permit an infinite number of shapes to be recognised (hence the ability to read handwriting), schemas for combinations of letters that form words and combinations of words to form phrases permit extremely complex combinations of squiggles to be recognised. Further, additional schemas connect these squiggles to objects, events, and procedures permitting meaning to be derived. These schemas are acquired over very long periods of time and are all stored in long-term memory. In character and function, there is every reason to believe that schemas for reading are identical to the schemas acquired by chess grand masters for chessboard configurations. All skilled performance in complex domains requires the acquisition of countless numbers of schemas held in long-term memory.

From a multimedia perspective, knowledge is held in a schematic form in long-term memory whether it is pictorial or verbal, written, or spoken. Recognising chessboard configurations or written text is largely visual and requires visual schemas. Recognising where words begin and end in the continuous sound that constitutes speech requires auditory schemas. In all cases, that ability to appropriately categorise information requires immense numbers of schemas held in long-term memory.

While schema acquisition is a major form of learning it is not the only one. Material held in long-term memory can be processed either consciously or automatically (Kotovsky, Hayes, & Simon, 1985; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Once a schema has been acquired, further practice over long periods of time can permit it to be processed automatically without conscious control. Once the letters of the alphabet and their combination into words and phrases has occurred, further learning allows one to read without consciously considering those letters or even considering individual words and some combinations of words. Such processes have become automated and other activities can be engaged in such as attending to meaning. Again, automated schemas are held in long-term memory and can be either pictorial or verbal, spoken or written.

Working Memory

What does it mean to say some material can be processed consciously or automatically, or that some material has been learned with understanding or is not yet understood? Working memory and its interactions with long-term memory provide an explanation. When dealing with novel information, working memory has two severe limitations. Miller (1956) indicated that working memory is only able to hold about seven elements of information. It can probably process in the sense of combine, contrast, or manipulate no more than about 2–4 elements. On these numbers, the capacity of working memory when dealing with new information is severely constrained. The duration of working memory is also constrained. Peterson and Peterson (1959) found that without rehearsal, almost all the contents of working memory are lost within about 20 seconds.

What are the instructional design consequences of these working memory limitations? All instruction requiring learners to deal with novel information must be processed by a structure that is minute in capacity and that retains the new information for no more than a few seconds. These limitations should be a central consideration of instructional design. While the aim of instruction should be the acquisition of automated schemas, the execution of this aim requires a constant monitoring of the working memory consequences of any recommended procedure. Instructional designs that ignore working memory limitations are likely to be random in their effectiveness.

Many instructional design recommendations do ignore working memory limitations. As an example, any inquiry-based instructional design inevitably places a heavy load on working memory. For this reason, it is important to place human working memory limitations into a theoretical framework to facilitate a full understanding of the reasons for a limited working memory. Working memory limitations when dealing with novel information are not accidental. They are an essential concomitant of human cognitive architecture. Without those limitations, our cognitive mechanisms could not function. They are there for a purpose and that purpose directly impacts instructional design considerations.

Why Working Memory Is Limited

Consider a student learning a new task such as how to navigate the Web. The student is faced with a screen page containing many buttons each likely to represent a link to other pages and functions that also contain many more links and functions. The amount of information is massive, consisting of a large number of interacting elements. The student needs to learn how those elements interact. What is the consequence of clicking on one button as opposed to another?

Faced with such a complex task that imposes a heavy working memory load, it is natural to assume that if humans had evolved with a much larger working memory, we would be better able to deal with natural complexity. That assumption may be incorrect.

Consider the process by which the student has to learn which buttons on the screen to press in order to successfully navigate. It is a new task and so the student has no knowledge informing him or her of the procedures to be followed. Assuming there is no one present to provide direct guidance, the student must engage in problem solving to determine an appropriate procedure. Failing knowledge (either one's own or someone else's knowledge), a problem-solving search can only function by randomly proposing a step and then testing that step for effectiveness. That random component is quite unavoidable when dealing with novel material that necessitates problem solving. It has profound implications both for how our cognitive architecture is organised and for instructional design.

Consider a working memory such as our own that is severely limited in that it can only combine about four elements at any given time. There are many ways those elements could be combined but let us assume they are being combined using the logic of permutations. With four elements, there are $4! = 24$ permutations. It may be difficult to determine which of 24 permutations is best but it is likely to be possible. In contrast, assume a somewhat larger working memory that can handle 10, rather than 4, elements. With 10 elements, there are $10! = 3,628,800$ permutations. A cognitive architecture structured to test the relative effectiveness of millions of possibilities is likely to be unworkable. As a consequence, and paradoxically, a somewhat smaller working memory is likely to be more efficient than a larger one. We may have evolved with a limited working memory because a slightly larger, or worse, unlimited working memory may be counterproductive.

As was the case with long-term memory, these processes are directly analogous to those used by evolution by natural selection. A species faced with a changing environment may evolve to handle the new circumstances. The manner in which it evolves is not predetermined. It is heavily dependent on the variations to be found between members of the species. All variations between species and between individual members of species can ultimately be sourced to random mutations. In effect, whenever a mutation occurs, it is checked for effectiveness with effective mutations leaving more offspring and ineffective mutations leaving fewer or even no offspring. From an information-processing perspective, this process is indistinguishable from human problem solving, which also depends on random generation followed by tests of effectiveness. The underlying logic of both systems is identical.

General Instructional Implications of Working Memory Characteristics

Instructional implications flow from the suggestion that a student learning something new must use the same information-processing system as a species learning to adapt to an environment. Left to his or her own devices without assistance, a student learning, for example, how to navigate the Web, has no choice but to randomly try procedures and test them for effectiveness. Where knowledge is available, either from another person or source, or from long-term memory, it is likely to be used. Where it is not available, random generation followed by effectiveness testing is the only alternative. In its essence, all inquiry-based learning depends on a random generation followed by effectiveness testing procedure. It is likely to be a long, slow, and ineffective procedure for acquiring knowledge.

Once we understand that working memory capacity is small and why it must necessarily be small when dealing with novel information, we can begin to understand that a major function of instruction is to overcome the inevitable limitations of working memory. Having students learn in the same way as species evolve is fine if there is no alternative. Frequently, there are alternatives and a major function of instructional design is to find those alternatives. Many of those alternatives are discussed in subsequent chapters of this handbook.

Multimedia and Working Memory Limitations

Early work on working memory treated it as a single entity. Current theories, either explicitly or implicitly, assume that working memory consists of multiple streams, channels, or processors. Baddeley's (1992) working memory model is probably the most influential. It consists of a coordinating central executive and two subsystems: a visuo/spatial sketchpad for dealing with two- and three-dimensional objects and a phonological loop for dealing with verbal material. Generally speaking, the visuo/spatial sketchpad deals with vision while the phonological loop deals with auditory material such as speech. At present, while there is strong evidence, as discussed in the following text, for the two partially independent, subsystems, there is less evidence for the coordinating role of the central executive.

There are instructional consequences that follow from this division of working memory. Penney (1989), in a review, provided evidence that appropriate use of both subsystems can increase working memory capacity. While the increase is not additive in the sense that all of the information being processed by auditory working memory can be added to all of the material processed by visual working memory, there is a lesser but demonstrable increase and that increase supports the hypothesis of partially separate processors. The increase also can be used for instructional purposes. If instruction is designed to make use of multiple processors, learning can be facilitated (Mayer, 2001).

Relations Between Long-Term and Working Memory

Human cognitive architecture has evolved with an ingenious set of relations between long-term and working memory. The nature of those relations provides the centre-piece of human cognitive functioning and is critical to any theory of instructional design. The intellectual heights that humans have reached and to which they aspire are made possible by the manner in which information in long-term memory alters the characteristics of working memory.

The limitations of working memory were discussed previously. It must be emphasised that those limitations apply only to novel information fed to working memory through the sensory system (known as sensory memory). Information that has already been organised into schemas in long-term memory can also be fed into working memory. Neither the duration nor capacity limitations attached to novel information received from sensory memory applies to information from long-term memory. That information has no measurable limitations of either duration or capacity. It can be indefinite in size and duration. In effect, information in long-term memory vastly expands working memory. That expansion trivialises any biological differences between humans in the capacity of working memory. Basic differences between people in working memory capacity are likely to be irrelevant given the huge alterations in this processor that occur when it is dealing with organised information taken from long-term memory.

Historically, the influence of long-term memory on working memory dates back to the initial research on working memory. Miller's (1956) concept of chunking suggested that people could learn to "chunk" together elements of information that could be processed in working memory as a single element. While the concept of chunks was not explicitly connected with long-term memory because the distinction between working and long-term memory was articulated later, using current knowledge, chunking cannot occur without long-term memory. Chunks either reside in long-term memory or are formed using information held in long-term memory.

Atkinson and Shiffrin (1968) provided a model that delineated sensory, working, and long-term memory stores. That model is central to most subsequent treatments with information moving between the stores. In that model, we begin to see the influence of long-term memory on working memory although the major influence, the alteration of the characteristics of working memory by information in long-term memory, was not made explicitly.

Another major advance came from Ericsson and Kintsch (1995) with their concept of long-term working memory. They suggested that because the characteristics of working memory when processing information from long-term memory are so dramatically different to its characteristics when processing information from sensory memory, it is appropriate to assume a separate processor – long-term working memory.

In the current treatment, rather than assuming a separate processor that processes information in a qualitatively different manner depending on whether the information comes from sensory or long-term memory, the same working memory processor will be assumed irrespective of whether information comes from sensory or long-term memory, with its characteristics gradually altering as the novelty or familiarity of information alters (Sweller, 2003). At one end of a continuum, when dealing with unfamiliar information, working memory limitations are critical. They become successively less critical as familiarity increases, in other words, as more and more information from long-term memory is used. At the other extreme, when dealing with information incorporated in well-entrenched, automated schemas, working memory limitations become irrelevant. Thus, the extent to which working memory limitations matter depends on the extent to which the information being dealt with has been organised in long-term memory. The characteristics of working memory and the manner in which working memory functions is critically dependent on what has been stored in long-term memory.

Relations between working memory and long-term memory can also be used to explain understanding (Marcus, Cooper, & Sweller, 1996). Understanding occurs when all relevant elements of information can be processed simultaneously in working memory. Because of the limitation of working memory when dealing with novel information, if faced with new material that must be learned, there may be too many elements to simultaneously process in working memory. If the elements are essential, understanding can't occur until it becomes possible to process them. While studying the material, elements are organised and combined into schemas held in long-term memory. When schema construction and automation have progressed to the point where all of the elements essential to understanding the topic can be processed in working memory, understanding has occurred. Based on these interactions, understanding can be defined as the ability to simultaneously process required elements in working memory. On this definition, the relations and interplay between working and long-term memory are central to understanding.

As was the case when individually considering long-term and working memory, it is appropriate to consider the relations between the processors within an evolutionary framework. In the case of both evolution and human cognition, large amounts of information can only be dealt with after they have been appropriately organised. Prior to being organised, the amount of information that can be dealt with is necessarily very small. In the case of genetic information, huge amounts of organised information can be dealt with and transmitted from generation to generation but alterations to a genome are not and cannot be organised. Random alterations followed by effectiveness testing are unavoidable and so any viable alterations will be relatively minuscule. Similarly, a huge amount of schematically organised information held in long-term memory can and is used repeatedly but failing direct guidance through instruction, changes to long-term memory cannot be organised. Random proposals followed by effectiveness testing must be used and this procedure cannot result in rapid, massive, effective changes to long-term memory. Alterations must be small and a small working memory when dealing with new information is a consequence.

Schemas as a Central Executive for Working Memory

The relations between working and long-term memory go beyond long-term memory altering the characteristics of working memory. Schemas in long-term memory act as a central executive for working memory. They indicate what should be done, when it should be done and how it should be done. In other words, organised information in long-term memory directs the manner in which information is processed in working memory. It is ideally placed to do so precisely because it is organised. Thus, in this sense also, information in long-term memory alters the characteristics of working memory.

Not only do schemas act as a central executive, they are the only conceivable central executive. If schemas are not available, as occurs when dealing with new information, there is no alternative central executive to call upon. As previously indicated, when relevant information in long-term memory is not available, random generation followed by effectiveness testing is the only remaining alternative. Contrary to theories such as that of Baddeley (1992), there is no logical manner in which a central executive other than a learned central executive, can function (Sweller, 2003). Just as no central executive function can direct evolution by natural selection, similarly no unlearned central executive can direct information in working memory. In both cases, if previously acquired information is not available, decision making can only occur by random generation followed by effectiveness testing.

Instructional Consequences: Cognitive Load Theory

It was stated previously that schemas held in long-term memory constitute the only conceivable central executive for organising information. In one sense, that is not entirely true. Information provided by others can also act as a central executive. If there is no schema available, rather than randomly organising information and then testing for effectiveness, schemas held by someone else can be used to organise the information. In other words, other people's knowledge, imparted in either spoken or written form, can act as a central executive if one's own schema-based central executive is unavailable. Of course, other people's knowledge can only act as a central executive if it is available in a suitable form. Many instructional procedures explicitly recommend techniques that place a primary emphasis on random generation followed by testing. All inquiry-based recommendations fall in this category and are unlikely to act as a suitable central executive.

The alternative is direct, instructional guidance that provides a substitute for the missing schemas and allows learners to develop their own schemas without engaging in the difficult, time-consuming process of almost limitless random generation followed by testing. There is nothing in our cognitive architecture that suggests that a random generation and testing procedure should be superior to direct instructional guidance. Furthermore, how that direct instructional guidance is organised should also depend on the structures and characteristics of human cognitive architecture. Instruction that does not have as its primary aim the accumulation of knowledge in long-term memory through schema construction and automation and that does not consider working memory characteristics, is likely to be less than optimal. Instructors need to keep in mind that before learners faced with novel material can organise and incorporate it in long-term memory, they must process it using a limited working memory that includes partially independent channels for auditory and visual information. These characteristics of human cognitive architecture have implications for the design of instruction, especially multimedia instruction.

Cognitive load theory (Paas, Renkl, & Sweller, 2003, 2004, Sweller, 1999; 2003; Sweller, Van Merriënboer, & Paas, 1998) and the instructional principles it has generated are all based on these assumptions concerning human cognitive architecture. There are three categories of cognitive load discussed by the theory: extraneous, intrinsic, and germane cognitive load.

Extraneous cognitive load is caused by inappropriate instructional designs that ignore working memory limits and fail to focus working memory resources on schema construction and automation. There is a wide range of instructional design principles that are based on cognitive load theory. Each principle takes a commonly used instructional procedure, analyses it from the perspective of relevant aspects of human cognition, and then redesigns the instruction to reduce working memory load and increase schema construction and automation. The worked example (chapter 15 in this volume), split-attention (chapter 8), modality (chapter 9), redundancy (chapter 10), and expertise-reversal effects (chapter 21) are directly relevant to multimedia learning and because they are discussed in some of the following chapters will only be summarised briefly here. (A summary of other cognitive load effects may be found in Sweller, 2003.)

The worked example effect (e.g., Cooper and Sweller, 1987) is demonstrated when learners studying worked examples that provide a solution to a problem learn more than learners who are required to solve the equivalent problem. Searching for a solution during problem solving places heavy demands on working memory and those demands interfere with schema construction. A worked example, by reducing or eliminating search, reduces extraneous cognitive load and so facilitates learning.

The split-attention effect (e.g., Sweller, Chandler, Tierney, & Cooper, 1990) occurs when attention must be split between multiple sources of visual information that are all essential for understanding. A geometric diagram and its associated statements provide an example. The multiple sources must be mentally integrated before the instruction can be understood and the material learned. Mental integration imposes a heavy extraneous cognitive load that is reduced by physically integrating the multiple sources of information.

The modality effect (e.g., Tindall-Ford, Chandler, & Sweller, 1997) also occurs under conditions where multiple sources of information are essential for understanding and learning and where the visual information requires learners to split their attention. In the case of the modality effect, the extraneous cognitive load is reduced, not by physically integrating the sources of information but by presenting verbal material in spoken rather than written form. Cognitive load is reduced because the use of dual modality increases effective working memory capacity (as noted previously).

The redundancy effect (e.g., Chandler & Sweller, 1991) differs from the split-attention and modality effects in that it does not deal with multiple sources of information, all of which are essential for understanding and learning. Rather, it deals with multiple sources of information in which one source is sufficient to allow understanding and learning while the other sources merely reiterate the information of the first source in a different form. They are redundant. A diagram plus a statement that redescribes the diagram in words provide an example. Extraneous cognitive load is reduced and learning is facilitated, not by eliminating split-attention or using dual modality presentation but instead, by eliminating the redundant information.

The expertise reversal effect (Kalyuga, Ayres, Chandler, & Sweller, 2003) occurs when instructional procedures such as physically integrating multiple sources of information or presenting instruction in dual mode format first lose their advantage with increasing learner expertise and then become disadvantageous compared to split-source visual presentation. The effect occurs because information that is essential for novices becomes redundant for more expert learners. (There are other conditions under which the expertise reversal effect occurs, discussed in chapter 21.)

Intrinsic cognitive load is the cognitive load due to the natural complexity of the information that must be processed. It is determined by levels of element interactivity. For example, if someone is learning to translate some of the nouns of a foreign language, each translation can be learned independently of every other translation. One can learn to translate the word *cat* without learning to translate the word *dog*. In this example, element interactivity is low and so working memory load is low. In contrast, the elements that constitute other material may interact in the sense that one cannot meaningfully learn one element without simultaneously learning many other elements. For example, if learning the appropriate word order in English for the words *when learning a language*, one cannot attend to individual words to determine that *a language learning when* is inappropriate. One must consider all of the words and the relations among them because they interact. Element interactivity is high resulting in a high intrinsic cognitive load. While there are other reasons why learning can be difficult such as the material including a very large number of elements irrespective of whether they interact, understanding and learning high element interactivity material are difficult for a specific and important reason: Because high element interactivity material imposes a high working memory load.

Lastly, germane cognitive load (Paas & Van Merriënboer, 1994) is "effective" cognitive load. It is the cognitive load caused by effortful learning resulting in schema construction and automation. Providing learners with a variety of examples demonstrating a point increases cognitive load but the increase is germane in that it is likely to assist schema construction.

Extraneous, intrinsic, and germane cognitive load are additive. The aim of instruction should be to reduce extraneous cognitive load caused by inappropriate instructional procedures. Reducing extraneous cognitive load frees working memory capacity and so may permit an increase in germane cognitive load. Nevertheless, if intrinsic cognitive load is low, increases in germane cognitive load may be possible even with high levels of extraneous cognitive load because a low intrinsic cognitive load results in a relatively low total cognitive load. In other words, how one designs instruction may not be particularly important when dealing with simple material that can be easily understood. Even with poor instructional designs, working memory capacity may not be exceeded. Instructional design may only be critical when dealing with complex material that imposes a heavy working memory load due to its intrinsic nature. Adding a heavy extraneous cognitive load to a heavy intrinsic cognitive load may exceed working memory capacity whereas adding a heavy extraneous cognitive load to a light intrinsic cognitive load may not exceed capacity. As a consequence, the cognitive load effects due to extraneous cognitive load and summarised previously can only be demonstrated using material that is high in element interactivity (Sweller & Chandler, 1994; Tindall-Ford, et al., 1997). If element interactivity is low, material can frequently be understood and learned even if extraneous cognitive load is high. This effect is the element interactivity effect.

Conclusions

Instructional design that proceeds without reference to human cognition is likely to be random in its effectiveness. Until relatively recently, that lamentable state of affairs was unavoidable because our knowledge of human cognitive architecture was too sparse to effectively apply to instruction. The immense expansion of that knowledge, including suggestions concerning the evolutionary origins of human cognitive architecture, has altered the instructional design landscape. The limitations of working memory when dealing with novel information, the elimination of those limitations when dealing with well-known information, and the consequences of partially separate auditory and visual working memory channels all have profound implications for instructional design in general and multimedia instruction in particular. Those implications have changed and are likely to continue to change instructional procedures.

Glossary

Auditory working memory (or auditory processor): That component of working memory that deals with speech and other auditory information.

Automation (or automaticity): A process by which schemata held in long-term memory become sufficiently well-practiced to enable them to bypass, or to be processed without conscious use of, working memory. Automated schemata impose a minimal strain on working memory.

Cognitive architecture: The manner in which the cognitive structures used to learn, think, and solve problems are organised.

Cognitive load: The load imposed on working memory by information being presented.

Cognitive load theory: An instructional theory based on our knowledge of human cognitive architecture that specifically addresses the limitations of working memory.

Direct instructional guidance: Instruction in which procedures are directly demonstrated to learners. Can be contrasted with inquiry-based learning.

Dual-modality instruction: The use of both auditory and visual information under split-attention conditions. Can be contrasted with single modality instruction, normally presented in visual only mode.

Element interactivity: The extent to which elements of information that must be processed interact. If material that must be learned has high element interactivity, elements cannot be processed individually in working memory and so that material will be seen as complex and difficult to understand (see *intrinsic cognitive load*).

Inquiry-based learning: Instruction in which learners, rather than having a procedure demonstrated, are required to discover it themselves. Can be contrasted with direct instructional guidance.

Integrated instructions: Instructions in which multiple sources of information are physically integrated so that working memory resources do not need to be used for mental integration. Can be contrasted with split-attention instructions.

Intrinsic cognitive load: The cognitive load that is imposed by multiple, interacting elements (see *element interactivity*) that, because they interact, must be processed simultaneously rather than successively in working memory resulting in a heavy load.

Learning: Any change in long-term memory involving an accumulation of information.

Long-term memory: The cognitive structure that stores our knowledge base. We are only conscious of those contents of long-term memory that are transferred to working memory.

Redundant instructions: Instructions presenting the same information in different forms.

Schema: A cognitive construct that schematically organises information for storage in long-term memory. When brought into working memory from long-term memory, a schema allows us to treat multiple elements of information as a single element classified according to the way in which it will be used.

Sensory memory: The cognitive structure that permits us to perceive new information.

Split-attention instructions: Instructions in which multiple sources of information are not physically integrated so that working memory resources need to be used for mental integration. Can be contrasted with integrated instructions.

Visual working memory or visual processor: That component of working memory that deals visually with two- or three-dimensional objects.

Working memory: The cognitive structure in which we consciously process information. Notable for its severe capacity and duration limits when dealing with new information.

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Abstract

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