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Instructional Design Consequences of an Analogy between Evolution by Natural Selection and Human Cognitive Architecture

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Abstract. Evolution by natural selection may be characterized as a system in which a large store of genetic information will persist indefinitely while it remains coordinated with its environment but will continuously produce small random variations that are tested for environmental effectiveness. In any environment, effective variations will persist while ineffective variations will disappear. Similarly, human cognitive architecture includes a large store of information held in long-term memory that coordinates our cognitive activities. A very limited working memory tests the effectiveness of small variations to long-term memory with effective variations altering long-term memory while ineffective variations are lost. Both an existing genetic code and information in long-term memory provide a central executive that guides behaviour. Such a central executive is unavailable when an environment alters or when working memory must be used to deal with novel information. A major function of instructional design is to provide the otherwise missing structure of a central executive when dealing with novel information and to reduce that structural support as knowledge accumulates in long-term memory. Cognitive load theory both provides instructional design principles that would be difficult to devise without its particular view of human cognitive architecture and throws further light on that architecture.

Instructional design issues and human cognitive architecture are inseparably intertwined. Not only is no useable science of instruction feasible without knowledge of human cognitive structures, but instructional design issues can impact heavily on the development of our knowledge of cognitive structures. Knowing how students learn and solve problems informs us how we should organise their learning environment and without such knowledge, the effectiveness of instructional designs is likely to be random. Equally, discovering that some instructional designs are superior to others can provide insights into human cognitive architecture that may otherwise be difficult to achieve.

Cognitive load theory, with its close links between human cognitive architecture and instructional design, provides an example of the advantages of linking the two areas. The theory has used our knowledge of human cognitive architecture to generate a large number of instructional designs, some of which are unlikely to have been mapped without our knowledge of cognitive structures. More recently, the theory has begun to provide insights into human cognitive architecture that would have been difficult to achieve without knowledge of the instructional design principles afforded by the theory. This paper outlines some of the knowledge of both human cognitive architecture and instructional design generated by cognitive load theory (Paas, Renkl and Sweller 2003; Sweller 1999; Sweller, Van Merriënboer and Paas 1998; Van Merriënboer, Kirschner and Kester 2003).

Human cognitive architecture and its evolution

There has been a tendency for some cognitive theories to treat human cognition as a unique system, different from other natural systems on earth. As an example, for many, human problem solving activities are assumed to be qualitatively different from any other processes found on earth and as such, to define the essence of the human mind. This tendency is probably part of our historical assumptions concerning the uniqueness of the human intellect. In contrast, if we assume that human cognitive architecture evolved in the same manner as all other biological characteristics, it is unlikely that it has properties qualitatively different from those found elsewhere. Our ability to learn and solve problems may be superior to other animals on earth but is most unlikely to be qualitatively different. Accordingly, the probability may be slim that effective instructional designs can be found that assume cognitive processes such as, for example, a unique teachable/learnable general problem solving skill. If even the rudiments of such a teachable/learnable general skill cannot be found elsewhere, it is unlikely to be a central feature of human cognitive architecture and as a consequence, attempts to teach such a skill are likely to be futile. The following sections discuss aspects of human cognitive architecture and by finding analogues to processes required by evolution by natural selection, provide evidence for a general information processing system that underlies intelligent behaviour (Sweller 2003).

Long-term memory. It is suggested that the major, unique aspect of human cognitive architecture is a quantitative one – the size of human long-term memory – and that most other intellectual differences between humans and other species such as our ability to learn and solve problems, stem from quantitative differences in long-term memory. It is further suggested that the well-known processes used by evolution by natural selection bear a striking resemblance to the processes of the human cognitive system and that we have evolved to mimic those processes that drove our own evolution. Nowhere is the resemblance between evolution by natural selection and human cognitive architecture more apparent than in the way both systems use stored information.

Long-term memory consists of a large, relatively permanent store of information. The centrality of long-term memory to learning is obvious and indeed, definitional. If nothing has altered in long-term memory, nothing has been learned in any permanent sense. The centrality of long-term memory to problem solving and thought was much less obvious and required what may arguably be cognitive science's most important discovery. When De Groot's (1965) work on chess became available to an international audience (it had first been published in 1946), it altered our conception of human cognitive architecture. De Groot found that chess grand masters defeated less able players, not because they engaged in a more effective search for good moves or because they were better able to plan a more effective strategy, but because they recognised most of the board configurations that they encountered during a game and knew from previous experience which were the best moves for each familiar configuration. They did not have to work out the best move because they knew the best move. In other words, chess grand masters held tens of thousands of board configurations from real games and the moves associated with them in long-term memory. Evidence for this suggestion comes from De Groot's finding that chess grand masters were very good at reproducing board configurations taken from real games while less able players were much poorer. There may be no other differences between players of different skill levels. Chase and Simon (1973) confirmed this result and found no differences between less and more able players in memory of random board configurations. Chess problem solving skill derives from a huge amount of information held in long-term memory. It is that information, accumulated over many years, that distinguishes better from poorer chess players.

Information held in long-term memory similarly distinguishes more from less able problem solvers in all areas of human endeavour, including educationally relevant areas. In the late 1970s and 1980s, many studies demonstrated similar results to those of De Groot (1965) and Chase and Simon (1973) in a variety of curriculum areas (e.g. Egan and Schwartz 1979; Jeffries, Turner, Polson and Atwood 1981; Sweller and Cooper 1985). It is now widely accepted that expertise, including problem solving expertise, in any area, is at least heavily dependent and possibly solely dependent on knowledge held in long-term memory.

The information stored in long-term memory can be considered analogous to the biological information stored in a genetic code. A species' genome constitutes a huge and relatively permanent store of information that determines the biological characteristics of that species. On any measure (and there is no consensus on how the size of a genome should be measured), there is a massive amount of information stored in a genome. That large, permanent store of information will determine the biological characteristics of a species just as the large and relatively permanent store of knowledge held in long-term memory will determine the cognitive characteristics of an individual. Those cognitive characteristics consist of the areas in which the individual has greater or lesser expertise and the consequent behavioural patterns in the various contexts in which a person may find him or herself.

While more detailed instructional implications will be discussed below, the obvious, general implication can be stated now: The major function of instruction is to store information in long-term memory. Facilitating the acquisition of appropriately organised information in long-term memory is a major concern of cognitive load theory, discussed below. The theory has generated a series of instructional effects based in part on the assumption that instructional design should be structured to facilitate alterations in long-term memory.

Working memory. Working memory is the seat of consciousness and may be equated with consciousness. We are only aware of information in working memory. We are unaware of the much more extensive information held in long-term memory unless it is transferred, temporarily, to working memory.

Information can enter working memory by one of two routes: either from long-term memory in the case of previously learned material or as new information via sensory memory. The way in which these two sources of information are processed by working memory is vastly different leading to profound instructional design issues. Those instructional design issues are central to cognitive load theory which was formulated to deal with them.

When processing new information entering via sensory memory, working memory is transitory and very small in capacity. The transitory nature of working memory was demonstrated by Peterson and Peterson (1959). They found that if people are presented sets of unfamiliar combinations of letters to hold in memory, those letters can only be held for a few seconds without rehearsal. From an instructional perspective, that means when learners are presented with new information, that information is lost within a few seconds unless the instruction is designed to take into account and compensate for this characteristic of working memory when dealing with unfamiliar information.

The limited capacity of working memory when faced with novel information is equally dramatic. Miller (1956) in his well-known work indicated that working memory can hold no more than about 5-9 elements or chunks of information that have not been previously learned or combined, i.e. novel, unfamiliar information. That number is substantially less when information must be processed in the sense of combined, contrasted or worked on in some respect. Under such circumstances, working memory is unlikely to be able to process more than about two or three elements, depending on the precise nature of the required processing.

As was the case for the limited duration of working memory when processing novel information, the limited capacity of working memory has profound instructional consequences. Instructional designs that require learners to process more than a very few new elements of information at a time will fail. Again, successful instruction must be designed to take into account this characteristic of working memory. Cognitive load theory, discussed below, was formulated to take into account the limited duration and capacity of working memory when faced with novel information entering via sensory memory.

Not all information enters working memory through sensory memory. Information also enters working memory from long-term memory and such information has vastly different characteristics to those described above. Whereas there are severe capacity limits to the amount of information from sensory memory that working memory can process, there are no known limits to the amount of information from long-term memory that can be processed by working memory. Information is normally stored in long-term memory in organised form and there may be no limits to the amount of such organised information. For example, if we consider the information associated with the word "restaurant" it includes much of what we know of food, the preparation of food, eating, the serving of food, aspects of a financial system and its relation to goods and services, the architecture of buildings and furniture, social relations between humans etc. It may be difficult to list all of the information elements associated with the word "restaurant". These elements, appropriately organised, are all held in long-term memory. They can be brought in their entirety into working memory from long-term memory as a single element without overloading working memory in any way. The amount of familiar information that can be processed in working memory after storage in long-term memory can be barely compared to the amount of novel information from sensory memory that can be similarly processed. It has led theorists such as Ericsson and Kintsch (1995) to postulate a separate cognitive structure, long-term working memory.

It should be noted that not only does information in long-term memory determine the characteristics of working memory, it also determines the characteristics of sensory memory. What we see and hear is determined heavily by what we know. As an obvious example, our ability to distinguish where one object ends and another, adjacent object begins is dependent on our knowledge of the characteristics of those two objects. Without knowledge of the existence of the two objects, we may have difficulty perceiving them unless they are placed in a manner that makes them very distinct. Similarly, without knowledge of the sounds that constitute a foreign language, we cannot distinguish one word from another. That knowledge is held in long-term memory and determines what we perceive.

The characteristics of working memory can also be found in some of the operations of evolution by natural selection. The capacity limitations of working memory ensure that each alteration to long-term memory is slight. Similarly, individual alterations to a genome are also slight. Complex functions such as sight evolve over millions of years. They never arise as a single event. Indeed, the stability of a genome is exemplified by species that have survived essentially unaltered over millions of years. Similarly, because of working memory limitations, the contents of long-term memory alter slowly or in some areas, may not alter at all. If a person has learned to traverse from A to B, that knowledge may remain in long-term memory unaltered for indefinite periods.

From an instructional perspective it needs to be noted that the manner in which students process information will differ markedly depending on the extent to which that information has been previously organised in long-term memory. Students who have previously organised material in long-term memory may be readily able to process it in working memory. Students who have not organised the same material in long-term memory may find it impossible to process it in working memory. As a consequence, instructional designs that are very effective for novices may be quite ineffective for more expert learners, and vice-versa, because the working memory characteristics of novices and experts can barely be compared. Cognitive load theory was designed to provide guiding principles for dealing with students who have differing knowledge levels and so differing working memory characteristics.

Randomness. Why is the capacity of working memory so limited when dealing with new information coming from sensory memory? Sweller (2003) suggested that when dealing with new information, by definition, there are no knowledge structures available to indicate how the new information should be organised. Problem solving processes must be used to organise novel information and to the extent that previously acquired knowledge indicating how to organise elements of information is unavailable, random factors must be used. Learners must combine elements randomly and then determine which random combinations are useful in solving the problem. Failing knowledge, there is no substitute for such a random combination followed by effectiveness testing procedures.

If elements must be combined randomly, the number of elements that can be considered at any time is severely limited. As the number of elements increases, the number of possible combinations increases exponentially.

Using a problem solving process to determine which combinations of two or three elements are likely to be useful is quite feasible. Using the same process to determine which combinations of ten or more elements are useful may be quite impossible. Depending on how ten elements are to be combined, there may be literally millions of possible combinations. (For example, using the logic of permutations, 3! = 6 but 10! = 3,628,800.) Working memory may be limited when dealing with unfamiliar information in order to permit viable processes that organise that information to operate.

Random combinations of elements followed by tests of effectiveness are similarly central to evolution by natural selection. All biological variation including variations both between and within species can ultimately be sourced to random mutation. Just as working memory provides a mechanism to ensure that alterations to long-term memory are small because large random alterations are highly unlikely to be adaptive, so successful alterations to a genome are slight because large random alterations are highly unlikely to permit survival. Functions such as sight require a long, slow evolutionary process because the probability of all the information required for such a complex function being assembled as a single event by a random process is effectively zero. In contrast, the probability of sight occurring is increased if a large number of minor alterations are tested for effectiveness with only effective alterations used subsequently and with each effective alterations being added to previous ones. Similarly, a limited working memory ensures that large random changes to long-term memory do not occur since they are unlikely to be adaptive. Small changes, with each tested for adaptivity, can result in a large change over time that has a high probability of effectiveness.

Instructors need to be aware that without direct, instructional guidance, learners have no choice but to adopt a random generation of possible alternatives followed by tests of effectiveness. Instructors also need to be aware that while this process can result in effective learning, it can be excruciatingly slow and so require huge amounts of time. While it is the only way new knowledge through research can be obtained, there is no reason to use such a procedure in educational settings. Encouraging the use of a process that necessarily incorporates an essential random component seems pointless. Cognitive load theory provides alternatives.

Central executive functions. Why is randomness so central to both evolution by natural selection and human cognitive architecture? The lack of a central executive function to coordinate new information provides an answer. If there is no central executive to determine how new elements are to relate to each other, the only other procedure is to randomly combine elements and then test the effectiveness of the combination. Both evolution by natural selection and human cognitive architecture rely on this mechanism when faced with new circumstances requiring new ways of coordinating information. As indicated below, a highly effective central executive does become available when the two systems deal with familiar, as opposed to novel, information.

The evidence for an absence of a cognitive central executive function when dealing with novel information comes from two sources. The first is empirical. If a central executive exists to coordinate novel information, we should have evidence of its characteristics and its manner of operation. We should at least have some empirical evidence of how a cognitive central executive coordinates novel, unfamiliar information. That empirical evidence is largely missing.

A working memory theory such as Baddeley's (1992) theory postulates a central executive that coordinates the information dealt with by two subsystems, a visuo-spatial sketchpad to deal with two or three dimensional visual information and a phonological loop to deal with auditory information, primarily language. While much empirical work has led to considerable information about the two subsystems, far less work has been carried out on the central executive. That paucity of research could simply reflect the interests of researchers or the impenetrability of the central executive. Alternatively, it could also reflect the absence of such a structure. (It might be noted that if a central executive is eliminated from Baddeley's model, some of the attributes of the central executive in the model such as capacity and duration limitations must be transferred fully to the "subsystems" instead. For example, the limited capacity and duration of working memory can be considered to reside solely in the visuo-spatial sketchpad and the phonological loop rather than in a central executive.)

The failure to find empirical evidence for a central executive provides strong evidence against its existence. There may be stronger evidence. For a central executive to coordinate novel information, it must have rules indicating how that information is to be dealt with. But, because relations between elements of the information are unfamiliar, there can be no such rules. A central executive with no guiding principles will need a second executive to guide it. That second central executive will face the same problems as the first, requiring a third, etc. This infinite regress invalidates the entire concept. Instead, random combinations of elements followed by effectiveness tests can act as a substitute for a central executive. Of course, as indicated above, such a process necessarily dictates possible (and impossible) structures for human cognitive architecture. A limited working memory when dealing with novel information provides the most obvious example.

Evolution by natural selection would face exactly the same conundrum except a central executive for dealing with novel information has never been postulated. Indeed, the theory was proposed in order to explain biological processes and entities without the need for a central executive-like designer. Random mutation, followed by greater or lesser ability to reproduce, acting as an effectiveness test substitutes for a central executive.

Notwithstanding the above points, the bulk of both human cognitive activity and biological activity are governed by powerful, very effective central executives. They deal with familiar, organised, known elements of information rather than novel information. Acquired knowledge, held in long-term memory, has all of the characteristics expected of a central executive. That acquired knowledge organises our sensory world and determines our actions. What we think of and even how we think is overwhelmingly determined by our knowledge held in long-term memory. Our cognitive processes are coordinated by domain-specific knowledge acting as a central executive.

Consider some of the cognitive processes of a reader of this paper. He or she is first faced with a page containing an immensely complex set of squiggles. The reader knows that those squiggles need to be scanned line by line across from the top left hand corner down to the bottom right hand corner. The squiggles form discreet letters, a limited number of which are spaced together to form words that in turn combine into sentences and paragraphs. Meaning attaches to each of these elements in the sense that they relate to each other and to additional knowledge held in long-term memory. Ultimately, the entire set of squiggles contains meaning that can be related to other knowledge held in long-term memory. That meaning provides the ultimate justification for the exercise.

This complex set of cognitive processes could not proceed without being coordinated by a central executive. Knowing what to look at, when to look at it and what to do with it constitutes a very complex activity that must be coordinated and that coordination clearly requires a central executive function. A central executive is available but it is not a general, biological structure. It is a specific, learned structure. Over a very long period of time, we learn to read and that learned skill acts as a central executive. It tells us what cognitive activities, including perceptual and motor activities we must engage in to appropriately process the information on a page. It is a learned central executive. We have acquired similar functions for every cognitive activity in which we engage. Of course, it is not available when we must deal with novel information for which there is no or only partial knowledge in long-term memory. Under those circumstances, a different mechanism is required. As indicated above, that mechanism is not an undefined and probably undefinable general central executive. Instead, it consists of randomly combining elements followed by tests of effectiveness.

A close analogue to the processes described above can be found in evolution by natural selection. The biological activities of both individuals and entire species is heavily determined by their genetic code. That code acts as a central executive controlling biological activity. Of course, if an altered environment requires an alteration in biological activity and so an alteration in the genetic code, no central executive is available to control the changes in the code. Random mutation followed by effectiveness tests (natural selection) are the only available mechanisms. If the analogy between evolution by natural selection and human cognitive architecture is valid, these well-known processes can be used as a template to understand human cognition.

It has been suggested above that no central executive is available when novel information must be dealt with. In one sense, that is incorrect. Instruction can and should act as a substitute central executive. Indeed, one of the major instructional consequences that flows from our knowledge of human cognitive architecture and its evolution concerns appropriate instructional procedures given the absence of a central executive when dealing with novel information. If appropriate interactions between elements are unknown and so must be combined randomly and tested for effectiveness, then learning will be slow and clumsy. Unfortunately, many enquiry-based educational movements (e.g. Bruner 1961) have precisely this characteristic. An emphasis on having learners discover interactions between elements is an invitation to have them combine elements randomly. An absence of knowledge or a central executive leaves no alternative if instruction is organised in this manner. Using direct, instruction-based guidance rather than enquiry-based instruction can eliminate the problem. Such guidance can compensate for the missing central executive by indicating to learners precisely how elements interact.

In effect, rather than having knowledge in a learner's long-term memory acting as a central executive guiding cognitive processes, knowledge in another person's long-term memory can act as a central executive through written or oral communication. That knowledge in another person's long-term memory was either transmitted from a third or subsequent person's long-term memory, or was derived by a problem solving process with its random components. The initial alteration in the "discoverer's" long-term memory always requires random generation followed by testing just as is required by successful alteration in a genome. Once successful random generation and testing has occurred, the new information can be passed on indefinitely either as part of a genome or as human knowledge.

In this sense, instruction can at least partially take over the role of a central executive. Other peoples' knowledge, initially acquired slowly over very long periods of time using random generation followed by testing for effectiveness, subsequently can be used as a central executive to order unordered information that otherwise could never be organised and learned. Of course, instructional design must take into account the lack of an internal, cognitive, central executive when dealing with new material by appropriately structuring information. Cognitive load theory indicates techniques for accomplishing this aim.

Creativity. Enhancing the creativity of learners has been a goal of psychology and education for generations. It is an unrealised goal. After many false dawns based on claims of success that could not be replicated, it is clear that teaching learners to be creative in any meaningful sense is at the very least difficult and perhaps impossible. The lack of a clear theoretical base to guide consideration of the issue of creativity has the inevitable consequence of a field based more on enthusiasm than solid, understandable findings. We must at least consider the possibility that not only are there no established techniques for teaching creativity, but that the very concept makes little theoretical sense and if so, there may never be grounds for optimism that teachable/learnable creativity techniques will become available. The current analogy between evolution by natural selection and human cognitive architecture provides a base from which to consider the problem of creativity.

Evolution by natural selection is a creative system. The theory was devised and continues to be used to explain the creation of the many biological structures, functions and indeed, species that can be found in the natural world. All of the diversity found in life is assumed by evolutionists to have been created using the mechanisms postulated by the theory. That diversity is not only, to this point, beyond the ability of humans to classify fully (it is an ongoing scientific enterprise), some of the structures and functions are still beyond human understanding. We are quite unable to duplicate the processes found in most animal organs. Not only are we unable to duplicate the complexity of the human brain, we cannot even duplicate the processes of a mammalian kidney. Evolution has created structures still beyond our ability to understand, let alone create ourselves. It is a hugely successful, creative system.

While humans may not be able to match evolution by natural selection in terms of creativity, we have a very good grasp of its mechanisms. Furthermore, if, as suggested in the current paper, the processes of human cognitive architecture are analogous to the processes described by evolutionary theory, we may have a theoretical basis for understanding human creativity. Creativity occurs when a system permits random alterations to processes to be tested for effectiveness with effective alterations retained by the system and ineffective alterations jettisoned. This procedure may be universal, explaining all forms of creativity.

How can this system explain variations in human creativity? Random alterations to a knowledge base are presumably just as likely in one individual as another and yet some people are consistently more creative than others. The answer is in the size of a knowledge base. Alterations to a large knowledge base have the potential to generate ideas quite beyond the capabilities of a person with a much smaller knowledge base. In other words, differences in creativity between individuals are not due to differences in creative processes but rather, are due to differences in the knowledge bases to which the same creative processes are applied. If so, attempting to teach humans to be creative is likely to be as futile as attempting to teach evolution by natural selection to be creative. We can use instruction to assist learners in acquiring a knowledge base and that knowledge base can increase the probability of them being creative. If the current theory is valid, attempting to teach people to be creative in some general sense will fail.

Planning. It may be argued that planning for the future is an essential component of human cognition and of course, a lack of planning is central to evolution by natural selection. In fact, human planning is simply another example of the use of information stored in long-term memory. No planning can occur other than based on knowledge of past events. Planning is based on a prediction of future events but predictions of future events, like all human decision making, is made either on the basis of past events (i.e. knowledge held in long-term memory), randomly or most commonly, a combination of knowledge and random processes. As indicated above, there can be no other basic components to any human cognitive activity (excluding genetically programmed activity). Organising a plan cannot consist of more than organising elements of information taken from long-term memory in a manner determined by experience. Where information held in long-term memory provides no guide, random generation followed by testing is unavoidable.

Cognitive load theory

Establishing an analogy between human cognitive architecture and evolution by natural selection strengthens confidence in the validity of the structures postulated to constitute human cognitive architecture. From an instructional design perspective, it is essential that we know the characteristics of the relevant cognitive structures because an extensive knowledge of human cognitive architecture is required for a viable instructional science. In turn, if our knowledge of human cognitive architecture can be used to generate applications such as instructional design principles, that too can strengthen our confidence in the validity of the architecture. Cognitive load theory uses the cognitive architecture described above to generate instructional design principles.

The theory is explicitly based on those assumptions concerning cognition that are analogous to the basic assumptions of evolution by natural selection. Specifically, the theory assumes that: (a) The purpose of instruction is to build knowledge in long-term memory which is analogous to the building of a genome; (b) There are mechanisms to ensure that alterations to large stores of information (such as long-term memory or a genome) are small and incremental. In the case of human cognitive architecture, that mechanism is a limited capacity working memory when dealing with new information; (c) Alterations to an information store must be small because failing the acquisition of already organised information, alterations are random, and large, random alterations are unlikely to be functional; (d) Random rather than ordered alterations are inevitable in the absence of a central executive function determining the nature of the alterations.

Properly structured instruction takes these factors into account. It can provide a central executive function, eliminate the need for random generation, and so facilitate alterations to long-term memory. Instruction can permit other people's long-term memory to act as a substitute for random generation and effectiveness testing. Cognitive load theory provides principles for structuring instruction in a manner that facilitates the use of an instructional central executive function. A large number of such principles have been generated by researchers around the globe. This section summarises that work.

Worked example effect. If novices in an area are given a problem to solve, they are likely to learn something from the exercise of randomly generating moves and testing those moves for effectiveness, just as a genome can adapt to an environment by this procedure. Nevertheless, people should learn more in less time if they can use someone else's previously acquired knowledge by being shown the appropriate moves: in other words by being presented a worked example. Worked examples can be expected to reduce extraneous cognitive load by acting as an instructional central executive and so reducing the load on working memory, leaving more working memory capacity to acquire knowledge to store in long-term memory. Many experiments have demonstrated this basic worked example effect: Carroll (1994); Cooper and Sweller (1987); Miller, Lehman, and Koedinger (1999); Paas (1992); Paas and Van Merriënboer (1994); Pillay (1994); Quilici and Mayer (1996); Sweller and Cooper (1985); Trafton and Reiser (1993).

Completion effect. Rather than presenting learners with full worked examples, partially completed examples can be used with learners required to complete the missing moves. This procedure partially uses someone else's knowledge as a central executive to reduce random generation of moves and is as effective as using full worked examples (Paas 1992; Paas and Van Merriënboer 1994; Van Merriënboer 1990; Van Merriënboer and de Croock 1992; Van Merriënboer and Krammer 1987; Van Merriënboer, Schuurman, de Croock and Paas 2002).

Split-attention effect. If the central executive function of instruction is to be effective, the contained information should not require the use of unnecessary processing. Two sections of a genome may contain all of the information for a particular function but may not be functional until they are combined. Effectiveness may increase if they are combined into a single entity in the first instance. Inappropriately structured worked examples may be ineffective for the same reason.

There are many documented conditions under which worked examples are ineffective. One such condition is where the worked example consists of multiple sources of information that are unintelligible in isolation and so require mental integration before they can be understood. A geometric diagram and its associated statements provide an example. The need to mentally integrate the two sources of information imposes a cognitive load that interferes with learning. Physically integrating the diagram and statements into a single entity by placing the statements at appropriate locations on the diagram reduces the cognitive load. The split-attention effect is obtained by comparing physically integrated with unintegrated material and finding an advantage for the integrated versions. Furthermore, the affect can be demonstrated with any instructional material, not just worked examples (see Bobis, Sweller and Cooper 1993; Cerpa, Chandler and Sweller 1996; Chandler and Sweller 1992, 1996; Mwangi and Sweller 1998; Sweller, Chandler, Tierney and Cooper 1990; Tarmizi and Sweller 1988; Ward and Sweller 1990). As well as this spatial version of the effect, Mayer and Anderson (1991, 1992) demonstrated a temporal version.

Modality effect. Identical information, genetic or psychological, can normally be presented in a variety of forms. Some forms are easier to integrate and process than other forms. Rather than physically integrating two sources of information that are unintelligible in isolation, as occurs when demonstrating the split-attention effect, if one of the sources is verbal, that source can be presented in spoken rather than written form. Penney (1989) provided evidence that the use of dual modality presentations can increase working memory capacity. It should be noted that a modality effect is only obtainable under split-attention conditions, i.e., conditions in which the two sources of information are unintelligible in isolation and must be mentally integrated before they can be understood. It is not obtainable by randomly presenting some material in auditory and some in visual form or by presenting the same material in both written and spoken form (see the redundancy effect below). Demonstrations of the modality effect may be found in Jeung, Chandler, and Sweller (1997); Mayer and Moreno (1998); Moreno and Mayer (1999); Mousavi, Low, and Sweller (1995); Tindall-Ford, Chandler, and Sweller (1997). See Brünken, Plass and Leutner (2004, this issue) for evidence using secondary task analyses that the modality effect is due to cognitive load factors.

Redundancy effect. If a section of an information store, whether genetic or psychological, can fully act as a central executive, having another section of the store attempt to provide an identical function is likely to be counterproductive. If one set of genes permits sight to develop, having another set of genes governing sight through a different pathway and by different means is likely to be ineffective.

The split-attention and modality effects require material that consists of disparate sources of information that are unintelligible in isolation and must be mentally integrated before they can be understood. If different versions of the same material are presented, that can lead to the redundancy effect. There are several different types of redundancy (see Sweller 2003) but all rely on presenting learners with additional material that they must unnecessarily process in working memory. A diagram and text that redescribes the diagram provides an obvious example as does presenting the same material in written and spoken form. The redundancy effect is demonstrated when eliminating the redundant material improves learning (see Cerpa, Chandler and Sweller 1996; Chandler and Sweller 1991, 1996; Craig, Gholson and Driscoll 2002; Kalyuga, Chandler and Sweller 1999; Mayer, Heiser and Lonn 2001; Mayer, Bove, Bryman, Mars and Tapangco 1996; Reder and Anderson 1980, 1982; Sweller and Chandler 1994).

Imagination effect. A function or procedure that evolved many generations ago is likely to be fine-tuned and so more effective in a particular environment than one that evolved more recently. Similarly, if learners have learned enough to enable them to process learned material in working memory, having them do so by asking them to "imagine" or mentally practice the material facilitates additional learning more than having them simply engage in additional "studying" (see Cooper, Tindall-Ford, Chandler and Sweller 2001; Ginns, Chandler and Sweller 2003). The reverse effect is obtained with "study" instructions being superior to "imagine" instructions if learners have not learned the material sufficiently well to be able to process it in working memory (see the expertise reversal effect below).

Isolated interacting elements effect. Highly sophisticated biological functions such as, for example, sight, cannot evolve in a single step. Evolution by natural selection assumes that they evolve by a large series of very small steps. Very sophisticated procedures and concepts need to be learned in the same way even with the advantage of an instruction-based central executive.

Some material is complex in that it consists of many interacting elements of information that must be processed simultaneously in working memory before it can be understood. Such material is high in element interactivity (Sweller 1994). If the nature of the material is such that the number of interacting elements exceeds the number that can be processed by working memory, learning with understanding cannot occur. At least some of the elements must be processed in isolated fashion in working memory, then combined and stored as higher level elements in long-term memory, before being combined with further elements. By successively reiterating this process, full understanding can eventually occur. It can be hypothesised that by presenting such very high element interactivity material to learners in isolated form rather than in their full interacting mode, followed subsequently by the fully interacting mode, learning will be facilitated. This effect was obtained by Pollock, Chandler, and Sweller (2002). For very high element interactivity material, presentation as isolated elements followed by interactive elements was superior to two presentations in interactive mode.

Element interactivity effect. Evolution by natural selection was required to explain how complex functions and entire species arose. While it can explain minor variations between individuals, that has not been its primary function. Similarly, the instructional designs that flow from cognitive load theory are required for high but not low element interactivity material. An instruction-based central executive is more important if many elements must be coordinated simultaneously than if only a few elements must be coordinated.

The previous effects all assume that some inappropriate instructional designs are deficient because they impose a heavy, extraneous cognitive load that overloads working memory functions. If element interactivity is low, the intrinsic cognitive load associated with the material is low and working memory may be able to function satisfactorily irrespective of the above instructional design issues. If so, the above effects should disappear using low element interactivity material and reappear using high element interactivity material. This effect has been obtained for the split-attention, modality and redundancy effects (see Chandler and Sweller 1996; Sweller and Chandler 1994; Tindall-Ford, Chandler and Sweller 1997; Marcus, Cooper and Sweller 1996).

Expertise reversal effect. The extent to which an instruction-based central executive is required will depend on the extent to which a knowledge-based central executive is already available in the information store. If a knowledge-based central executive is already available, an instruction-based version will be redundant and may interfere with additional learning. Similarly, once the genes for a particular function are established and effective, evolving a new set of genes for the same function is likely to be ineffective.

While the element interactivity effect is concerned with the characteristics of the material being presented to learners, the expertise reversal effect is concerned with learner characteristics. All of the above effects can be demonstrated with novices unfamiliar with area because the novel instructional designs were intended for commencing students. It is easy to assume that the same instructional designs will remain effective as students' levels of knowledge increase. In fact, information presented to novices, in whatever form, while initially essential, can be expected to become less essential with increased knowledge and may eventually become fully redundant. As a consequence, an instructional design that may lead to one of the effects described above may first lose its advantage over a conventional design and with further increases in levels of expertise may become less effective than a control group. As expertise increases, material that is essential for novices may become redundant and so impose an extraneous cognitive load compared to instruction that does not include the material, resulting in the expertise reversal effect (Kalyuga, Ayres, Chandler and Sweller 2003). There are now many experiments demonstrating the effect (see Kalyuga, Chandler and Sweller 1998; Yeung, Jin and Sweller 1998; Kalyuga, Chandler and Sweller 2000; Kalyuga, Chandler, Tuovinen and Sweller 2001; Kalyuga, Chandler and Sweller 2001; Tuovinen and Sweller 1999; McNamara, Kintsch, E., Songer and Kintsch, W. 1996).

Guidance fading effect. Rather than eliminating an instruction-based central executive when a knowledge-based central executive becomes available, it may be more effective to slowly fade the instruction-based central executive as the knowledge-based executive develops, in the same way as biological functions that are no longer relevant to a species, fade away over generations. The guidance fading effect provides a test of this possibility. The effect is a logical amalgam of the worked example, completion and expertise reversal effects. It assumes that as levels of expertise increase, the full worked examples associated with the worked example effect can decrease, to be replaced by the partial worked examples associated with the completion effect. These completion problems, in turn, can be replaced by full problems once sufficient knowledge has been accumulated. The guidance fading effect is obtained when this procedure is superior to one in which fading is not used (see Renkl 1997; Renkl and Atkinson 2003; Renkl, Atkinson and Maier 2000; Renkl, Atkinson, Maier and Staley 2002).

Goal-free effect. There is one condition under which an instructionally-based central executive may be unnecessary and random generation of moves followed by effectiveness testing can be successful. If a problem is structured so that moves may be made easily and all random moves made are useful, problem solving may be effective. Goal-free problems meet these criteria. Solving conventional problems during learning imposes a heavy cognitive load. In order to solve a problem, the problem solver must consider the current problem state, the goal state, differences between the two states, find problem solving operators that can reduce those differences and maintain track of any subgoals that have been established. These activities can easily overload working memory. Goal-free problems, rather than requiring the problem solver to find a value for a particular goal (e.g. "find a value for Angle ABC", "calculate the final velocity of the car") replace these specific goals with non-specific goals such as "find the value of as many angles as you can" or "calculate the value of as many variables as you can". Such non-specific or goal-free problems reduce working memory load because the complex procedure described above for solving a conventional problem is substituted by a procedure that simply involves finding a set of givens that will allow something to be calculated. The goal-free effect occurs when goal-free problems result in more learning than conventional problems and has been demonstrated on many occasions (Ayres 1993; Bobis, Sweller and Cooper 1994; Burns and Vollmeyer 2002; Geddes and Stevenson 1997; Miller, Lehman and Koedinger 1999; Owen and Sweller 1985; Paas, Camp and Rikers 2001; Sweller 1988; Sweller and Levine 1982; Sweller, Mawer and Ward 1983; Tarmizi and Sweller 1988; Vollmeyer, Burns and Holyoak 1996). It needs to be noted that because they provide no central executive guidance to problem solvers, goal-free problems should only be constructed using problems with a limited number of possible moves and where all moves have educational significance.

Conclusions

Without knowledge of human cognitive architecture, instructional designs are likely to be random in their effectiveness. The use of human cognitive architecture to generate instructional design principles through cognitive load theory has provided an appropriate theoretical base and resulted in instructional designs that would otherwise be difficult to devise. Furthermore, by considering how and why human cognitive architecture evolved with its particular characteristics and by considering the information processing characteristics of both evolution by natural selection and human cognitive architecture, insights can be gained which sharply clarify instructional design principles. The manner in which we attempt to encourage creativity in humans may alter once we consider the creativity exemplified by evolution by natural selection.

The effect is reciprocal. Not only does human cognitive architecture affect instructional design, instructional design principles also throw light on human cognitive architecture. The overwhelming importance of long-term memory to all aspects of human cognitive functioning with, for example, the characteristics of working memory changing dramatically with increased knowledge in long-term memory become starkly obvious when considered in the light of instructional design principles. A combination of evolutionary theory, human cognitive architecture and instructional design may exceed the sum of its parts.

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