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Discussion of 'Emerging Topics in Cognitive Load Research: Using Learner and Information Characteristics in the Design of Powerful Learning Environments'

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SUMMARY

Cognitive load theory began by using our knowledge of human cognition to devise instructional procedures. Insofar as those procedures have been successful, they have strengthened the cognitive theory that gave rise to them. Indeed, it has been possible to expand our knowledge of cognition by studying the manner in which information can be successfully presented to learners. As a consequence, today, cognitive load theory spans a range from the evolutionary origins of human cognitive structures to the instructional consequences that flow from those structures. In this discussion I will begin by outlining five principles that give rise to the cognitive architecture basic to cognitive load theory. I will then discuss the papers of this issue in light of this theoretical framework. Copyright © 2006 John Wiley & Sons, Ltd.

NATURAL INFORMATION PROCESSING SYSTEMS AND HUMAN COGNITIVE ARCHITECTURE

Human cognition is a natural information processing system. This class of information processing systems can be found in nature. There are many natural information processing systems other than human cognition with evolution by natural selection providing what is probably the best known and best specified system. Such systems rely on several common principles that are essential and irreducible in the sense that the elimination of any one of the principles will render the system ineffective. While there are different ways of characterising those principles (e.g. Sweller, 2003, 2004), in this paper five principles common to natural information systems will be discussed.

1. *The information store principle*. In order to permit their behaviour to adapt to complex environments, natural information processing systems require a very large information store that governs the bulk of the activities of the system. A genome provides that information store in the case of evolution by natural selection. Similarly, human long-term memory is sufficiently large to govern the bulk of human cognitive activity.

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2. *The borrowing principle*. Because natural information stores are so large, a procedure to rapidly acquire information is required. The borrowing principle provides such a procedure. Almost all of the information held in the store of a natural information processing system is borrowed from other entities. In the case of biological evolution, that process occurs either by asexual or sexual reproduction. Asexual reproduction involves a perfect or near perfect copying (borrowing) of a genetic code. In contrast, sexual reproduction is a constructive process. While the genetic code of offspring are borrowed almost entirely from their ancestors, each individual is a novel 'construction' of its mother and father and so different from both. Similarly, almost all information in human long-term memory is borrowed from another long-term memory either through imitation, listening or reading. While information is borrowed from another individual, that information is rarely, if ever, copied exactly. Rather it is a construction or combination of the information currently in long-term memory and the new information being borrowed from another long-term memory. There are inevitable random components in the combination of information elements inherent to the borrowing principle. The precise manner in which a particular set of male and female genetic codes combine or the manner in which old information in long-term memory and new information combine will have random components. Schemas are constructed in this way.
3. *The randomness as genesis principle*. The borrowing principle re-organises information, it does not create new information. New information is created via the randomness as genesis principle. All biological differences between species and between individuals of a species can be sourced back to a series of random mutations. A random generate-and test-procedure is used. A new genetic code is randomly generated and tested for effectiveness. New information that is effective is retained, while ineffective information is jettisoned. Similarly, all information in human long-term memory that has not been made available via the borrowing principle is generated randomly during problem solving. While the borrowing principle is a major mechanism of problem solving in that when faced with a problem we will normally attempt to solve it by using previously learned schemas, sometimes those schemas are not available. In the absence of appropriate schemas, either the problem solver fails to solve the problem or novel moves are generated via a random generate-and test-procedure with successful moves retained and unsuccessful moves jettisoned. Failing the availability of information through the borrowing principle, the randomness as genesis principle is the only other means by which new information can be obtained. Indeed, as is the case for biological evolution, this principle is the genesis of all new information.
4. *The narrow limits of change principle*. The random components of both the borrowing and randomness as genesis principles require that the generation of new information is a slow, incremental process. Large amounts of useful, new information are not and cannot be generated rapidly by a random mechanism. Useful mutations occur slowly over many generations. In human cognition, working memory is severely limited in capacity and duration but only when dealing with novel information. Due to combinatorial explosion, a large working memory capable of handling many unorganised elements simultaneously would have no function.
5. *The environment organising and linking principle*. Once information has been organised in the information store, the limits associated with the narrow limits of change principle disappear. Huge amounts of either genetic or cognitive information can be used to organise and link to the environment. Accordingly, there are no known limits when working memory deals with organised information from long-term memory in order to

permit us to interact with our environment. Information in long-term memory (or a genome) has already been tested for effectiveness and so there is no need for it to be limited. This principle permits us to function and act in our environment.

These principles provide a base for cognitive load theory. They indicate that the function of instruction is to accumulate usable information in the long-term memory store and indeed, that learning can be defined as a change in long-term memory; that learning can normally be assumed to occur via the borrowing principle and so the proper function of instructional design is to be concerned with how written, spoken and diagrammatic information should be presented; that teaching learners via a procedure that emphasises discovery or any form of instructional constructivism is likely to be futile because of the randomness as genesis principle; that information must be structured to take account of the narrow limits of change principle as expressed by a limited working memory; and lastly, that once it is organised in long-term memory, huge amounts of information can provide a powerful base via the environment organising and linking principle. That base permits us to interact in the very complex and sophisticated fashion required of human activity.

Instructional experiments based on cognitive load theory explicitly or implicitly assume these principles. If the principles are valid, they indicate which categories of instruction can be expected to be effective. I will use cognitive load theory to discuss the work reported in this special issue in the remaining part of this paper.

In a continuation of an interesting and rapidly developing line of research, Ayres (this issue) looked at the isolated-interacting elements effect and its interaction with the expertise reversal effect using mathematical error profiles. In his first experiment he confirmed that learning aspects of algebra using isolated elements was easier than learning the same rules in an integrated fashion. In a second experiment, using error rates, he found an interaction between levels of expertise and whether presentation used an isolated or interacting format. For less knowledgeable learners, an isolated presentation format was slightly superior but for more knowledgeable learners an integrated format was considerably better. Interestingly, the more knowledgeable learners indicated a higher cognitive load for the integrated than isolated format. This result was attributed to the learners having a higher germane cognitive load when faced with the integrated format. While this suggestion can explain the result, if we are to use such explanations we will need empirical techniques to distinguish between germane, intrinsic and extraneous cognitive load. At present these three categories of cognitive load are largely theoretical constructs rather than measurable entities. Some degree of measurement is possible if we keep two constant and vary only the third. Any difference in performance can be logically attributed to the category of cognitive load that was varied. If more than one category of cognitive load needs to be varied, as occurred in this experiment, then they need to be independently measured. At present, such measures are unavailable.

Olina, Reiser, Huang, Lim, and Park (this issue) hypothesised that providing learners with cues would reduce extraneous cognitive load while presenting problems in a random order would increase germane cognitive load. With respect to the cue hypothesis, the more learners are provided with important information by instructors (borrowing principle) and the less they must randomly test which problem-solving move might be effective (randomness as genesis principle) the more they should learn. Furthermore, they must learn which moves are appropriate for which problems irrespective of the order in which the problems appear. (Note that the random presentation of problem types is unrelated to random search when solving a problem.) While lower ability learners showed some sign of conforming to these hypotheses using measures of perceived mental effort, there were no performance differences due to the minimal learning obtained under all conditions. Accordingly, with respect to the interesting hypotheses, the results are indicative rather than conclusive. Ensuring instructional materials sufficiently match learner knowledge levels to permit appreciable learning is a difficult but essential pre-requisite to obtaining cognitive load effects. Unless researchers are very familiar with both the relevant materials and populations being dealt with, extensive pilot studies to match materials and populations are frequently required.

Van Gerven, Paas, van Merriënboer, and Schmidt (this issue) tested for interactions between the modality, variability and age effects. Applying cognitive load theory to the important problem of instructional procedures associated with ageing effects was initiated by this research group. A significant modality effect was obtained on cognitive load but not performance measures and a possible variability effect was obtained on performance measures. There were no interactions between any of the effects including the effect of age. The nature of the problem solving materials may account for these results. One of the characteristics of most puzzle problems is that they massively magnify the differences between the borrowing principle and randomness as genesis principle. While it can be difficult to discover the solution to a puzzle via the randomness as genesis principle during problem solving, it is frequently trivial to understand and learn that solution via the borrowing principle by having the solution shown in a worked example. Water-jug problems fall into this category. While solving these problems can be difficult, worked examples demonstrating solutions to water-jug problems are likely to be very easy to understand and learn resulting in a very low intrinsic cognitive load. Low intrinsic cognitive load materials do not normally demonstrate cognitive load effects due to a low total cognitive load. Instructions presented in a dual-modality format may have been easier to understand than single modality instructions but irrespective of the presentation format, the solution to the problems may have been readily understood and learned resulting in no performance differences due to cognitive load factors.

Seufert and Brünken (this issue) tested the effects of the presence or absence of hypertext links crossed with the presence or absence of additional explanatory information. In terms of learning efficiency they found that the presence of hypertext links without additional explanations had negative effects. The effects were positive when the links were associated with additional explanations. The absence of links with or without additional explanations were approximately equal and neutral in their effects. These interesting results can be interpreted in the context of the theory presented above. Providing hypertext links to learners who have insufficient knowledge to determine a navigational structure places additional emphasis on random decisions (randomness as genesis principle) and so has negative implications for learning unless additional guidance in the form of explanations provides useful information via the borrowing principle. I believe this paper provides a good example of the importance of providing instruction via the borrowing principle rather than the randomness as genesis principle. Novices should be given appropriate information and shown appropriate sequences rather than left in the discovery mode that is an inevitable concomitant of hypertext.

Kalyuga's (this issue) paper expanded his important work on rapid assessment for instructional purposes. The expertise reversal effect suggests that instructional procedures should alter as expertise develops. In order to determine whether expertise has developed to the point where instruction should change, we need techniques that can rapidly indicate levels of expertise. In previous work, the technique used was to present learners with a problem state and ask them to indicate the next move. The move they chose could be used to provide information on schemas stored in long-term memory and instruction could be altered accordingly. In the current paper, as well as verifying this technique, subjective ratings of task difficulty were also used to provide an efficiency measure allowing efficiency levels rather than just performance levels to be used to determine instructional procedures. Results indicated that the two adaptive instructional procedures using performance alone or performance and subjective ratings of task difficulty (efficiency) were superior to a non-adaptive procedure but did not differ from each other (there was a slight indication that efficiency was superior.) At this point, based on these results, we can only conclude that using performance as the sole measure during adaptive instruction is just as good as using the more complex efficiency measure—an instructive finding.

Van Merriënboer, Kester, and Paas (this issue) have provided an important theoretical position paper on issues associated with learning complex tasks. Most of the work within a cognitive load theory framework has been concerned with reducing extraneous cognitive load to permit an increase in germane cognitive load. An implicit assumption is that complexity is not so high that most or all working memory resources must be devoted to handling intrinsic cognitive load. Increasing germane cognitive load by increasing example variability can become self-defeating under exceptionally high intrinsic cognitive load. Van Merriënboer et al. suggest that there are at least two possible solutions. The first, which they reject because of its negative effects on transfer, is to reduce variability to at least allow learning to occur. As an alternative, they suggest that attempts to artificially reduce intrinsic cognitive load have been affective and should be used. I find the argument plausible. Nevertheless, it may be too early to reject germane cognitive load reducing techniques just yet. I accept that reducing variability and so reducing transfer performance should be avoided but am not sure whether experimental attempts have been made to initially reduce variability and then increase it as expertise increases. Theoretically, that should work but would require testing. My concern is that with a sufficiently high intrinsic cognitive load it may be quite counterproductive to introduce techniques to increase germane cognitive load until sufficient working memory capacity has become available with increasing expertise.

Research using cognitive load theory is a vibrant, active enterprise around the globe. The papers of this issue provide both theory and data attesting to the strength of this continuing work.

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