

Natural information processing systems

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Abstract: Natural information processing systems such as biological evolution and human cognition organize information used to govern the activities of natural entities. When dealing with biologically secondary information, these systems can be specified by five common principles that we propose underlie natural information processing systems. The principles equate: (1) human long-term memory with a genome; (2) learning from other humans with biological reproduction; (3) problem solving through random generate and test with random mutation; (4) working memory when processing novel information with the epigenetic system managing environmental information; (5) long-term working memory with the epigenetic system managing genomic information. These five principles provide an integrated perspective for the nature of human learning and thought. They also have implications for the presentation of information.

Keywords: cognitive architecture, cognitive load theory, information processing systems, long-term memory, working memory, random generate and test, evolution, genetic system, epigenetic system, mutation.

Introduction

The suggestion that the development of human knowledge and biological evolution by natural selection share a common underlying base has had a considerable ancestry. That ancestry may stretch back to Darwin (1871), based on some interpretations of his text. More recently, Campbell (1960), Dawkins (1976) and Popper (1979) have clearly articulated an analogy between the processes of biological evolution and knowledge development. Current work in this area emphasizes relations between behavioral, cultural and biological evolution (e.g., Aunger, 2000; Boyd and Richerson, 1985; Gintis, in press; Mesoudi, Whiten and Laland, in press). In a similar vein, Siegler (1996) proposed that the acquisition of knowledge during cognitive development was analogous to biological evolution. Furthermore, recent evidence that cultural evolution has consequences for the biological evolution of species (Baumeister, 2004; Danchin, Giraldeau, Valone and Wagner, 2004) suggests that genetic and cultural evolution may not only be analogous but interconnected, with each influencing the other.

In much of this work, while human cognition is implicitly recognized as being central, an explicit analysis of relevant aspects of human cognitive architecture is missing. If knowledge development follows biological evolutionary principles, then the mechanisms of human cognition and the structures that constitute human cognitive architecture should incorporate the processes and functions of evolution by natural

selection. In this paper we suggest that both human cognition when dealing with certain categories of knowledge and evolution by natural selection provide examples of natural information processing systems and that such systems can be specified by a series of basic principles that detail the mechanisms of the system. We will begin by indicating to which categories of knowledge the concept of natural information processing systems can be applied.

Biologically primary and biologically secondary knowledge

Geary (2002, 2005, in press) has distinguished between biologically primary and biologically secondary knowledge. Primary knowledge applies to categories of information that we have evolved to acquire and use. Learning to listen to and speak a native language, learning to interact socially with other humans and learning to use general problem solving strategies that apply to a wide range of problems provide examples of primary knowledge. Biologically secondary knowledge applies to categories of knowledge that may have become culturally important relatively recently. We have not had time to evolve specific mechanisms to deal with biologically secondary information. Rather, we can adapt primary knowledge and its acquisition to assist in processing secondary knowledge. Virtually all of the knowledge for which we require schooling consists of secondary knowledge. Learning to read and write provides a very clear example of secondary knowledge. We have not evolved to read and write and so the manner in which reading and writing is learned differs markedly from the manner in which listening and speaking develop.

Very large amounts of primary knowledge can be acquired easily, rapidly and unconsciously. We do not require specific cultural institutions and procedures to acquire such knowledge. It will be acquired automatically by all normal members of a functioning society. In contrast, secondary knowledge must be explicitly taught and learned via culturally organized procedures and institutions such as educational institutions. Without appropriate institutions and procedures, secondary knowledge will not be acquired by most members of a society. Thus, all normal members of a society will learn to listen and speak simply as a consequence of being members of the society. In contrast, very few members of a society learn to read and write unless the society has organized deliberate procedures to facilitate such learning. For most individuals, learning to read and write will not occur without deliberate cultural assistance because, unlike listening and speaking, we have not evolved to automatically acquire these skills.

The mechanisms by which biologically primary knowledge are acquired can be assumed to be specific to the category of knowledge. Our ability to recognize faces or learn the sounds of language are likely to be distinct. In contrast, our ability to acquire biologically secondary knowledge must be general because by definition, we have not evolved a capacity to acquire any particular category of that knowledge. We do have a capacity consisting of procedures, possibly related to intelligence, to acquire general secondary knowledge. Those procedures are required by any natural system that needs to process a variety of categories of information and the remainder of this paper will be concerned with the relevant processes.

Principles of natural information processing systems

Natural information processing systems can be found in nature. Like all information processing systems, their function is to organize information that governs the activity of entities incorporated by a system. Natural information processing systems direct the activities of natural entities such as living organisms. There are many ways of specifying the underlying logic of natural information processing systems but in this paper we will focus on five basic principles (see Table 1) and indicate how they apply to both human cognition and to evolution by natural selection.

Table 1. Natural information processing system principles

Principles	Cognitive case	Evolutionary case	Function
<i>Information store principle</i>	Long-term memory	Genome	Store information for indefinite periods
<i>Borrowing and reorganizing principle</i>	Transfer information to long-term memory	Transfer information to a genome	Permit the rapid building of an information store
<i>Randomness as genesis principle</i>	Create novel ideas	Create novel genetic codes	Create novel information
<i>Narrow limits of change principle</i>	Working memory	Epigenetic system handling environmental information	Input environmental information to the information store
<i>Environmental organizing and linking principle</i>	Long-term working memory	Epigenetic system handling genetic information	Use information stored in the information store

The information store principle

All natural information processing systems include a central store of information that determines the bulk of activities of the system. Because the environments in which natural information processing systems function are usually complex, a very large store of information is required to handle the many conditions faced. As a consequence, the size of the information store of natural information processing systems is frequently too large and complex to measure in any more than very approximate terms.

The contents of long-term memory provide the store of information for human cognition and as a consequence, the bulk of human cognitive activity is directly determined by long-term memory. The biologically primary knowledge associated with what we see, hear, and think is governed by what we have previously learned and stored in long-term memory and that primary knowledge, in turn, can be used to acquire and store large amounts of biologically secondary knowledge. Initial evidence

for the importance of long-term memory in human activities where it had previously not been considered important came from de Groot's (1946/1965) work on the game of chess. Chess is a game of problem solving and it was easy to assume that long-term memory played a minor role in successful chess playing. de Groot's finding that chess masters could much more accurately reproduce board configurations taken from real games than week-end players, along with Chase and Simon's (1973) replication and demonstration that the difference disappeared using random board configurations, altered our understanding of human cognition. No reliable differences between chess experts and novices attributable to other factors have been found. Accordingly, it is reasonable to assume that the only difference between expert and novice chess players is due to experts having stored in long-term memory large numbers of chess board configurations along with the best moves associated with each configuration. Novices must attempt to work out the best move. Experts know the best move.

This result has been replicated in a variety of contexts using a variety of different materials (e.g., Egan and Schwartz, 1979; Jeffries, Turner, Polson and Atwood, 1981; Sweller and Cooper, 1985). The findings suggest that long-term memory does not just provide the obvious function of permitting us to *remember*, it is central to all cognitive activities including ones where memorization is not an obvious component. What a chess grand master sees when he or she looks at a chess board configuration is different to what a less able player sees just as what a person familiar with an office layout sees when entering an office is likely to be vastly different to what a person who has grown up in a forest and unfamiliar with offices sees when entering an office. The perceptual differences are due to differences in the contents of long-term memory. Similarly, problem solving moves that are obvious for a person familiar with a situation may be impossible to contemplate for someone unfamiliar with that situation. Long-term memory can both inform us of the characteristics of a situation and tell us how to deal with it in the same way that a chess grand master's long-term memory allows him or her to recognize a board configuration and the most appropriate moves associated with it.

If long-term memory has a central, critical function in cognition, it must be huge to enable it to deal with the myriad of situations we face. Attempting to measure such an entity is a formidable task, the more so since we have no appropriate metric. The only attempt of which we are aware was conducted by Simon and Gilmarin (1973). They limited their measure to the number of board configurations a chess grand master is able to recognize and suggested that the number is between 50,000 and 100,000. Since chess is only a part of life even for a chess grand master, the total capacity of long-term memory is likely to be massive.

Evolution by natural selection is equally reliant on the information store principle. In genetics, organized information determines the production of proteins and resides in the genome. A genome is the total complement of an organism's and/or species' genes and is central to genetic activity with evolutionary change focused on genomic change. In cognition, if there is no change in long-term memory there has been no learning. Similarly, if there is no change in a species' genome, there has been no evolution. Evolution means genomic change.

All genomes contain massive amounts of information and as was the case with long-term memory, while there is no agreed procedure for measuring that information, all conceivable measures indicate a very large information store (see, for example, Portin, 2002 and Stotz and Griffiths, 2004, for discussions of techniques for measuring the size of a genome). However they are measured, all genomes appear to require thousands or even billions of units of information in order to allow life to survive and

evolve. Thus a genome, like long-term memory, is a large information store that governs complex activity, through very complex processes. That large information store lies at the heart of natural information processing systems.

The borrowing and reorganizing principle

To fulfill its role, an information store must obtain large amounts of information. In natural information processing systems the borrowing and reorganizing principle provides the required mechanism. We suggest almost all of the semantic information held in an individual's long-term memory has been borrowed from the long-term memory of other individuals (Boyd and Richerson, 1985). (Episodic memory is likely to depend on individual perceptual experience.) Humans imitate other people, listen to what they say and read what they write. These activities have the function of transferring information from the long-term memory of one person to the long-term memory of another in order to build the information store. Physical devices such as books or electronic storage must frequently be used as intermediaries in this transmission but all physically stored information initially came from an individual's long-term memory with the common intention of transfer to someone else's long-term memory.

While most information in long-term memory is borrowed, it is rarely, if ever, borrowed without reorganization, either at the time it is borrowed or subsequently. The borrowing and reorganizing process by which information is built in long-term memory is constructive. Previous information is combined with new information to construct a new representation with schema theory frequently used to describe the process (e.g., Chi, Glaser and Rees, 1982). A schema permits us to classify multiple elements of information according to the manner in which we will use them. For example, we may have a schema for a particular class of problems that permits us to classify the problem elements according to the solution that is appropriate for that problem. Chess players may classify board configurations according to the categories of moves appropriate for each configuration and it is that knowledge that permits them to reproduce briefly seen board configurations.

The process of combining new information with previous information has a random component with random generation followed by tests of effectiveness providing the mechanism. New information must be incorporated into previously acquired schemas and the consequent new construct must be tested for effectiveness. Because there is no way of determining whether the new construct is effective prior to its construction, random generation followed by tests of effectiveness are required (c.f. Simonton, 1999).

Evidence for the importance of the borrowing and reorganizing principle comes from the worked example effect. In the many experiments demonstrating this effect, learners who were presented worked examples to study rather than the equivalent problems to solve were better able to solve subsequent test problems (Carroll, 1994; Cooper and Sweller, 1987; Miller, Lehman and Koedinger, 1999; Paas, 1992; Paas and van Gog, 2006; Paas and van Merriënboer, 1994; Pillay, 1994; Quilici and Mayer, 1996; Reisslein, Atkinson, Seeling and Reisslein, 2006; Sweller and Cooper, 1985; Trafton and Reiser, 1993; van Gog, Paas and van Merriënboer, 2006). Learners presented mathematics or science worked examples to study, in effect, were borrowing problem solutions from other people while learners presented with problems to solve were devising their own solutions. Worked examples, by indicating an appropriate solution, reduce or eliminate random problem solving attempts. The more substantial

learning following the study of worked examples demonstrates the effectiveness of the borrowing and reorganizing principle.

The instructional use of worked examples when learning to solve problems is a form of imitation. The recent discovery of a mirror neuron system in both monkeys (Gallese, Fadiga, Fogassi, and Rizzolatti, 1996) and humans (Grafton, Arbib, Fadiga, and Rizzolatti, 1996) for motor action provides physiological evidence for the importance of imitation in human cognition. The mirror neuron system is an observation-execution matching system that fires when an individual either observes or executes an action. The fact that the system activates when observing others as well as when acting oneself indicates the importance to human cognition of observing the actions of others.

The mirror neuron system is involved in imitation. Iacoboni, Woods, Brass, et al. (1999) tested the consequences of asking people to make finger movements using several different sets of instructions. In one case, they were asked to imitate a hand in which a finger was lifted while in other cases a cross appeared above the finger that was to be lifted or a signal associated with lifting a particular finger was presented. The authors found that the mirror neuron system became active under all three conditions but a larger signal intensity was obtained for the imitative than the two non-imitative conditions. Iacoboni et al. also found that the system became active when people were asked to merely observe rather than observe and act under the three conditions. Further work has found that the mirror neuron system not only fires when an action is observed or signaled, it also fires when people listen to sentences describing actions (Tettamanti, Buccino, Saccuman et al., 2005).

We can conclude that imitating other people's actions either directly seen or inferred from speech or signals is an important method of obtaining information – sufficiently important for us to have evolved physiological mechanisms specifically to handle imitation. While our evolved tendency to imitate is biologically primary, there is no reason to suppose that the knowledge acquired is necessarily primary. The same evolved tendency to imitate is likely to apply to biologically secondary information. Imitation by humans may be universal whether it involves a simple physical action probably based on primary knowledge or a complex mathematical procedure based on secondary knowledge. We are physiologically organized to use the borrowing and reorganizing principle.

The borrowing and reorganizing principle is deeply entrenched in biological evolution. When one generation reproduces the next, the new generation borrows genetic material from the parent generation. Asexual and sexual reproduction provide two mechanisms of information transmission with substantially different information processing characteristics.

During asexual reproduction, a single individual passes a copy of all of its genome to its offspring. That genome can be copied and repeatedly passed on to new individuals during a process that seems to have no equivalent in human cognition because of the limited role reorganization plays in asexual reproduction. Theoretically, there is no variation in the offspring produced by asexual reproduction with all the information available to one generation also available to the next. In fact, two sources of variation can occur. The first, mutation, will be discussed under the next principle. The second provides several examples of the borrowing and reorganizing principle. Variability, through the exchange of genetic information, can occur in simple, asexually reproducing organisms like bacteria and viruses. There are three mechanisms that transfer genes between such individuals, with the details of the processes different from those involved in sexual reproduction (Redfield, 2001). 1. Bacteria can directly transfer

genetic material between two individual cells that join temporarily (a process which may be considered as the bacterial version of sexual reproduction). One cell donates its DNA and the other receives the genes. 2. Bacteria can alter their genomes by absorbing DNA from the environment and incorporating pieces into their own chromosomes. The cell is now a recombinant: its chromosome containing DNA obtained from two different cells. 3. Viruses that infect bacteria can transfer bacterial genes from one host cell to another. The process results from by-products generated during the infection by the virus.

In all these situations, information is borrowed and reorganized. As will be noted below with respect to sexual reproduction, each of these processes is likely to have a random component. Which genetic material is borrowed by these mechanisms and when it is borrowed is likely to be random. If the new material is adaptive, it will persist in subsequent generations. The techniques of reorganization described above occur in asexually reproducing organisms. Of course, asexual reproduction typically only involves borrowing by direct copying without reorganization.

While asexual reproduction does not usually reorganize information, sexual reproduction always and necessarily involves reorganization of information. During sexual reproduction, two cells are needed to reproduce offspring with each parent cell providing genetic material. This procedure has three basic and closely related information processing consequences. First, each new individual is a “construction” of its parents’ genetic material rather than a replication. Second, the process of sexual reproduction, by its very nature of fusing genetic material from two individuals, eliminates the possibility of exact reproduction and thus, unlike asexual reproduction, the material borrowed by the offspring always varies from the information possessed by the parents. In other words, reorganization is an essential part of the process. Third, not only are offspring genetically different from their parents, they are almost always different from each other (with the exception of identical siblings). Sexual reproduction is a technique for increasing the diversity of genetic information in a species with incremental alterations to the genetic information passed from generation to generation and it is that increased diversity that provides sexual reproduction with its advantage over asexual reproduction (e.g., Hamilton and Zuk, 1982).

In contrast to asexual reproduction, the evolutionary more recent sexual reproduction is closely analogous to the constructive processes of schema formation. As is the case for human cognition, there are unavoidable random components to sexual reproduction and it is those components that provide the variability generated by sexual reproduction. There are two main phases during sexual reproduction: the formation of male and female sex cells followed by the union of a male and a female sex cell. During both of these stages, genetic material is randomly reorganized, resulting in limitless variation, such that offspring will always be unique, with the partial exception of identical siblings.

There are three other important genetic processes that use the borrowing and reorganizing principle.

1. Most human genes contain two types of segments: one type codes for polypeptides (protein sub-units), the other has no protein coding function. Following the first step of gene expression (when the DNA code is transcribed into RNA), splicing of the original gene code occurs by excising the non-coding sections and then joining the coding sections in a way that will ultimately form the template for a particular protein. However, the coding RNA sequences can be spliced in alternative ways, thus rearranging the order of the coding sections and thereby coding for a different protein. As a consequence of splicing, one gene can produce more than one

protein. The alternate arrangement or splicing of codes becomes important when the same information needs to have a different function at different times, such as during the development of an organism or when the same information must be used to provide very high levels of diversity (Modrek and Lee, 2002). Thus, by the process of alternative splicing, under new environmental conditions and new requirements of the organism, new proteins with new, potentially useful, functions can be formed. It has been suggested that the process of alternative splicing is associated with evolutionary change (Modrek and Lee, 2003). The process is relevant to the borrowing and reorganizing principle because, as is the case with sexual reproduction, new information is not created directly. Rather, previously created information is borrowed and rearranged.

2. Viruses may provide one of the techniques by which non-coding sequences are inserted into DNA. Viruses can reproduce only inside other cells, using the genetic machinery of the host cells. Viruses inject their own genetic material into the host cell and copies of the viruses are made using the host DNA. Over time, some parts of the viral DNA may remain in the nuclei of some host cells. It has been suggested that these remnant pieces of DNA, which previously had coding capabilities, may have randomly inserted into the host DNA and have lost their coding potential. They now make up the non-coding segments (i.e. segments that do not code for protein) of the nuclear DNA molecules and may have regulatory functions (Rogozin, Babenko, Fedorova, et al., 2003; Turner, 2001; Weinzierl, 1999). This process also provides an example of the borrowing and reorganizing principle.

3. Another method of rearranging stretches of DNA occurs when sections of the DNA move (mobile genetic / transposing elements) from one location to another within the genome and so alter the output of many genes. This movement is more likely to occur in active regions of DNA chains (Jablonka and Lamb, 1995; 2005) and the activation of transposable elements has been shown to occur in stressful circumstances (McClintock, 1984). Again, the new information resulting from the rearrangement has been built by “borrowing” previously created information. It should be noted that both alternative splicing and mobile genetic elements are controlled by the epigenetic system, discussed below.

Reorganizing previously organized information in these ways does not guarantee, of course, that the newly organized information will be adaptive. There is an aspect of random generate and test (see next principle) in both alternate splicing and mobile genetic elements. For the moment, the similarity of these genetic mixing procedures and the manner in which the human cognitive system will combine previously acquired information to generate new information needs to be noted. For example, whenever a problem is solved by analogy (e.g., Gick and Holyoak, 1980, 1983), information from the source analogue is combined with information from the target problem to produce a new problem solution. That attempted solution may or may not provide an actual solution and so the analogy needs to be tested for effectiveness. Whenever knowledge in one area is combined with knowledge in another area, new information is produced that is equivalent to gene splicing and mobile genetic elements.

The borrowing and reorganizing principle is the major mechanism by which natural information processing systems provide individuals with large information stores, either cognitive or genetic. The principle permits the rapid acquisition of huge amounts of information that could not otherwise be acquired. Furthermore, both biological evolution and human cognition are structured to reorganize that information at the time it is borrowed, test the effectiveness of the resultant reorganization and retain or jettison it depending on the outcome of the test. While the vast bulk of

cognitive and genetic information held by an individual is acquired via the borrowing and reorganizing principle, it is not the only source of information. New information is created via the next principle, the randomness as genesis principle.

The randomness as genesis principle

Strictly speaking, the borrowing and reorganizing principle reorganizes rather than creates new information although, of course, reorganization does involve creativity. Nevertheless, a distinction does need to be made between reorganizing previously created information and an original act of creation that results in new information. A procedure for creating new knowledge is required because for a variety of reasons, useful, previously organized information obtainable via the borrowing and reorganizing principle may not be available. Consequently, natural information processing systems need distinct procedures for, on the one hand, borrowing and reorganizing previously generated information and for creating new information on the other hand.

Humans create new information during problem solving. The problem solving strategy that has undergone the most detailed study is means-ends analysis (Newell and Simon, 1972). This strategy was extensively analyzed using computer modeling during the 1970s and 80s (e.g., Sweller, 1988). In essence, the strategy requires a problem solver to repeatedly consider a current problem state, consider the goal state, extract differences between them and find a problem solving operator that can reduce those differences. Successful problem solutions can result in the creation of new knowledge that can be stored in long-term memory for subsequent use.

A close analysis of a means-ends strategy or, indeed, any problem solving strategy intended to discover new solution procedures will reveal that random generation followed by tests of effectiveness is central to the strategy. Consider a problem solver who has extracted differences between a current problem state and the goal state using a means-ends strategy. The next step is to find a problem solving operator that will reduce those differences. That process is straightforward if the problem solver either has knowledge in long-term memory indicating which problem solving operators might be used to reduce the differences or has access to knowledge in someone else's long-term memory. For example, competent elementary algebra problem solvers will know that if faced with the problem, $(a + b)/c = d$, solve for a , that multiplying both sides by the denominator c will reduce differences between the current and desired goal states. Prior knowledge can be used to generate this move but while the relevant knowledge may be strengthened through automation (Kotovsky, Hayes and Simon, 1985), new knowledge is not generated.

In contrast, consider a problem solver who has just learned the relevant rules (problem solving operators) of algebra. The problem solver does not have schematic knowledge in long-term memory indicating which moves are relevant to solving this problem. Under these circumstances, failing the receipt of information from others, we suggest the only viable strategy is to randomly generate a legal move and test it for effectiveness by observing whether the move has the desired effect of reducing differences between the given and goal states. Failing knowledge in long-term memory, there is no procedure available for determining the effects of a possible move prior to selecting that move. Accordingly, random selection is the only procedure available. In order to determine whether a move will reduce differences between the given and goal states a problem solver must randomly select it and either mentally or physically test it for effectiveness.

If the randomly selected move has the effect of reducing differences between the given and goal states, both the move and those states may be remembered on subsequent occasions obviating the need for random selection. In this manner, new information has been generated that can become part of the information store. Furthermore, this process provides the genesis of all new knowledge. The knowledge that we acquire from others via the borrowing and reorganizing principle had to be generated in the first instance by the randomness as genesis principle. Without this principle, basic, new knowledge cannot be generated.

It must be emphasized that random move generation during problem solving will only be used in the absence of any knowledge for ranking moves. If, for example, in the absence of complete knowledge, sufficient knowledge is available to rank a series of plausible alternatives, that incomplete knowledge will be used to generate moves. Nevertheless, under at least some circumstances, knowledge may be available to generate two or more possible moves that cannot be ranked on the basis of that knowledge. Under these circumstances, there is no available mechanism to choose a move to test other than random choice. Evidence for random choice under these circumstances comes from errors during problem solving. When faced with unfamiliar problems, most moves are likely to result in dead-ends, a result that may be difficult to explain under conditions other than random generation.

Evolution by natural selection uses a structurally identical procedure to human cognition to generate new information. New information is created by mutation (changes in DNA) using a similar procedure to humans solving a novel problem. As is the case during problem solving, because mutations are random, most are not adaptive and lead to “dead-ends”. While random generation is central, because most randomly generated mutations are not adaptive, random generation must be followed by tests of effectiveness.

The “problem” faced by all living organisms is survival and reproduction in a particular environment. Survival and successful reproduction provide evidence of effectiveness. As is the case with human cognition, there is no a priori system available to determine whether a possible mutation is likely to be useful. That determination only can be made after the event with successful mutations leading to increased offspring and unsuccessful mutations leading to decreased offspring. Furthermore, this process of mutation is the genesis of all biological variation. During asexual reproduction, apart from the probably rare borrowing of information from other cells as indicated previously, there can be no other source of variation. With respect to sexual reproduction, all the variation between the male and female genetic material (DNA), can be sourced back to a series of mutations. Without those mutations, the male and female DNA would be identical, resulting in no benefits of sexual over asexual reproduction. In other words, the advantages of the constructive processes that are integral to the borrowing and reorganizing principle rely on a series of prior mutations that occur according to the randomness as genesis principle.

For a mutation to be inherited from one generation to the next in sexually reproducing organisms, the change must be within the sex cells. If the change is in a normal body cell, then only a subgroup of cells in the individual will be affected but the mutation will not be passed on to the offspring organisms. This modification of sex cells is the basis of evolution. There are different kinds of mutations and their impacts vary. As might be expected of a random process, many mutations are deleterious, some are adaptive and some are neutral with selection pressures having no net effect.

While mutations are normally considered to be random, Jablonka and Lamb (2005) have suggested that in some situations mutations may occur in a non-random

manner, providing an increased survival advantage. For example, in some bacteria, mutations increase throughout the whole genome at a particular time, such as during stressful conditions. In some other organisms (e.g., meningitis causing bacteria and animals which use venom for capturing prey or for defense) there is a consistently increased mutational rate by a factor of hundreds or thousands over the average in a particular section of the genome where coding is for products that require much diversity. Another type of non-random mutation (in the bacterium *Escherichia coli*) occurs at a 5 – 10 times the average rate in defined sections of the DNA when environmental conditions change. In this case, the environment initiates mutations in those DNA sections that code for products that can assist the organism to cope in the new conditions.

These differential rates of mutations can be compared to differential rates of change in long-term memory due to only certain types of problems being attempted. Humans are more likely to engage in problem solving in areas that they perceive as being relevant to them and it is in those areas that alterations in long-term memory due to successful problem solving can occur.

Despite the effects of mutations, most variations in sexually reproducing organisms arise as a result of sexual reproduction, rather than due to changes introduced by spontaneous mutations (Strachan and Read, 2004). In other words, not only does the borrowing and reorganizing principle provide most of the information in a genome, it also provides most of the variability. If the human cognitive system functions in an analogous manner, most new information may originate via the borrowing and reorganizing rather than the randomness as genesis principle. Nevertheless, it needs to be remembered, that this information is only new in the sense that it consists of new combinations of old information. The differing entities that constitute those combinations originally arose due to the randomness as genesis principle. Similarly, during problem solving, most information is either borrowed from elsewhere or indirectly created by reorganizing previous information. Only when these processes fail to provide a solution is the randomness as genesis principle used.

It may seem paradoxical that the order demanded of natural information processing systems has randomness as its base; that the ultimate origin of ordered information is randomness. This paradox has resulted in randomness playing little part in most cognitive theories. The paradox is reduced when it is remembered that randomness is one partner in a duality: (a) random generation and (b) tests of effectiveness. Order is established by testing randomly generated possibilities. Thus, despite the centrality of randomness in natural information processing systems, randomness as genesis provides the origin of all organized information in this class of systems. Nevertheless, because randomness is central to natural information processing systems, it has further structural implications that are discussed next.

The narrow limits of change principle

The borrowing and reorganizing and the randomness as genesis principles are the two “learning” mechanisms by which natural information processing systems alter the information held in an information store. The randomness as genesis principle is the ultimate source of all novel information and is dependent on random generation followed by tests of effectiveness. The borrowing and reorganizing principle transfers information generated by the randomness as genesis principle to new stores but during the transfer process can combine that information with information from other stores

resulting in new information. This process of combination also includes a random component followed by tests of effectiveness.

The centrality of random processes in the accumulation of information has structural consequences. The greater the emphasis on random generation, the less information can be dealt with. Assume a system dealing with 3 elements that must be combined using the logic of permutations. Assume this system has no prior knowledge of how the elements should be combined and so any of the $3! = 6$ possible permutations may turn out to be effective. In other words, since there is no prior knowledge, all 6 permutations are candidates for effectiveness testing. Assuming one or more of the permutations is effective, a random generation and tests of effectiveness process will not take long to be successful.

In contrast, assume a system dealing with 10 elements resulting in $10! = 3,628,800$ possible permutations. If there is no knowledge of which permutations are more likely to lead to success, then random generation of possible permutations in order to test them for effectiveness will not be feasible without massive amounts of time. If there is knowledge that, for example, it is advantageous for 8 of the elements to be combined in a particular way, then the problem reduces to one that is identical to a system dealing with only three elements because eight of the elements can be treated as a single element.

From this analysis, it can be seen that a time-constrained system cannot function if it must deal with more than a few elements that need to be randomly combined. Using random generation, the probability of finding appropriate combinations (unless most combinations are appropriate) for more than a few elements is unlikely. Accordingly, the system needs to be organized in a manner that prevents more than a few elements to be considered at any given time. The capacity limitations of working memory when dealing with more than a very limited number of novel items provides a structural limit to the number of items that can be dealt with and so eliminates the above problem of a combinatorial explosion as the number of elements increases (e.g., Cowan, 2001; Miller, 1956). As a consequence of this limitation, changes to the information store driven by the randomness as genesis principle are limited. Recall, that this principle applies when knowledge is absent and problem solving processes with their random components are required. A limited working memory ensures that large, rapid, random changes to long-term memory do not occur. Such changes to an information store are likely to be dysfunctional and are prevented by a limited working memory.

The borrowing and reorganizing principle uses previously organized knowledge and to the extent that knowledge is previously organized, the problem of a combinatorial explosion is reduced. Accordingly, working memory is able to handle vastly more information using the borrowing and reorganizing principle than the randomness as genesis principle. Nevertheless, because the constructive processes used by the borrowing and reorganizing principle have a random component, working memory is limited even when learning occurs via the borrowing and reorganizing principle. Showing someone how to do something appropriately organizes much of the information and can vastly reduce the random components of attempting to organize all of the information for oneself. Despite this reduction in randomness, combining newly presented information with information already present in long-term memory does have random components that also require working memory limitations. These working memory limitations reduce the extent that untested information enters the long-term memory store.

The narrow limits of change principle applies equally to biological evolution because rapid, random changes to a genome will be equally dysfunctional as rapid random changes to long-term memory. Minor mutations in the genome can occur with minimal effects. Mutations in certain parts of the genome are more deleterious than in others and in general, if a large number of mutations occur at once, the offspring organism is less likely to be successful (Strachan and Read, 2004). For successful mutations to become well established in the population, small genetic changes over many generations with each change tested for effectiveness will be required.

For these reasons, mutation is rare. The error rate during human DNA replication is relatively small, with a mutation rate of approximately 2 bases in 100 million according to Giannelli, Anagnostopoulos and Green, (1999). The rate of mutation is low because of the existence of monitoring mechanisms such as corrections and proof reading systems. The low rate of mutation limits the rate of evolutionary change in the same way as a limited working memory limits changes to long-term memory.

Working memory provides an intermediary for information flowing from the environment (via sensory memory) to the information store, in this case long-term memory. Similarly, there are interactions between the environment and the sequence of bases in the DNA where the environment is defined as everything external to the DNA. Those interactions are not controlled by the DNA-based genetic system but rather, by the epigenetic system. The epigenetic and genetic systems are distinct (Jablonka and Lamb, 2005). While they can act independently, usually they interact.

By providing an intermediary between environmental information and the genetic system, the epigenetic system may provide a similar role in biological evolution that working memory plays in cognition. Indeed, new conceptions of biological evolution seem to be moving that field in directions that bring it closer to well-known concepts in human cognition such as working memory and its relations to long-term memory. West-Eberhard (2003) indicated that adaptive novelty frequently is not initiated by random mutation but rather, is initiated by environmental change affecting a phenotype. The environment, through the epigenetic system (a system that is not emphasized by West-Eberhard) can dramatically alter phenotypes of organisms with an identical genotype. For a given phenotype, which subsequent random mutations are adaptive and so added to a genome will depend on the particular environment in which the organism is found. Analogously, which problems and problem solving moves are attended to and so which aspects of long-term memory are altered by working memory during problem solving will depend on which problems are presented by the environment.

There are a number of epigenetic mechanisms associated with information flowing from the environment to the genetic system. One mechanism is based on chromatin (a complex formed from DNA and protein) and is independent of the DNA base sequences in that the activity is outside the DNA chain of bases. Environmental factors such as heat stress (Love and Kenney, 1999) and starvation (Moraes, de Campos Vidal, Guaraldo and Mello, 2005), can affect the structure of chromatin. Chromatin can be altered by the extent to which it is condensed (tightness of folding) and the extent to which it is methylated (holding varying quantities of the methyl chemical group). The degree of chromatin condensation and of methylation affect the activity of a relevant region of DNA, that is, whether a gene is active or not. In a region where the chromatin is highly condensed and methylated, the gene will not be expressed. In other words, the gene will be turned off. Such genes have less chance of being mutated (Turner, 2001). Thus, the epigenetic system influences not only gene activity but the probability that the region will undergo genetic change (Jablonka and Lamb, 1995; 2005).

This aspect of the epigenetic system “encourages” mutation in some areas of a genome and relatively speaking “discourages” mutations in other locations. Similarly, working memory activity will encourage problem solving and so result in long-term memory alterations with respect to some areas but not other areas. As has been previously noted (randomness as genesis principle), there are some mutations which appear to be non random (Jablonka and Lamb, 2005). Those mutations may be directional, a condition comparable with that in problem solving where the contents of working memory determine which problems will be attempted. As a consequence, some areas of long-term memory are more likely to be altered by problem solving than other areas. Similarly, some DNA areas are more likely to be affected by mutation than other areas and whether a mutation occurs may depend on the epigenetic system. For example, a particular sequence of bases that may be more easily mutated may be present in the cells and the epigenetic mechanism which turns on the gene, would, in times of environmental stress also “turn on production of mutation in that gene” (Jablonka and Lamb, 2005, p. 323). This link between epigenetic and genetic mechanisms can both enable the mutation and ensure it is not repaired thus allowing it to remain.

In this section we have indicated that the randomness as genesis principle requires limitations on processing novel information, leading to the narrow limits of change principle. Working memory with its capacity limitations provides the required structure in human cognition. Novel information is processed by working memory and working memory must be limited precisely because the information is novel. Through its control of mutations, the epigenetic system appears to play the same role in evolutionary biology. While we know that successful mutations are rare and limited, to this point as far as we are aware, there have been no suggestions of epigenetic limitations equivalent to the limitations of working memory. If the analogy between the epigenetic system and working memory is valid, we might expect such limitations to be found.

Working memory and the epigenetic system not only obtain information from the environment that has consequences for the information store. The information store sends information to working memory and the epigenetic system. That information is vastly different in character to the information received from the environment. It permits activity appropriate to the environment and is the subject of the next and last principle.

The environmental organizing and linking principle

The narrow limits of change principle suggests that because random generation is unavoidable when dealing with novel information, there is no advantage to having a large working memory. The reason random generation must be used when dealing with novel information is because there can be no central executive to indicate how novel information should be organized (Sweller, 2003). The very fact that it is novel precludes the possibility of a central executive or indeed, any workable procedure other than random generation followed by tests of effectiveness that can act as a substitute for a missing central executive. There are advantages to having a large working memory if a central executive is available because the central executive can be used to organize information and eliminate the need for random generation.

Knowledge in long-term memory provides a central executive that indicates (1) what should be attended to, (2) how information should be processed and (3) what actions should be taken. Failing knowledge, a viable central executive is not available.

Knowledge does more than provide a central executive to organize information. Because information is organized by knowledge, there is no need for working memory limits and the associated problem of randomly organizing information and testing a particular organization for effectiveness. There may be no limits to how much organized information can be processed in working memory. Ericsson and Kintsch (1995) refer to this process in terms of a structure – long-term working memory. In contrast to short-term working memory, this structure permits large amounts of information to be rapidly processed but only if that information has previously been organized in long-term memory. As a consequence, knowledge changes the characteristics of working memory from a limited capacity, limited duration structure to one that either has vastly increased limits or perhaps, in effect, has no limits (Simon, 1990).

It is this characteristic of organized information that provides working memory with its ultimate function. Unlimited amounts of organized information in long-term memory can be brought into working memory in order to organize the environment and determine actions that are appropriate to the environment. Determining those actions can involve mental simulation of potential behavioral solutions without the risks that may be associated with a behavioral test. Hence, the environmental organizing and linking principle provides the ultimate reason for human cognition. It indicates why we can transfer large amounts of organized information from long-term to working memory. The complex actions required of humans need this principle to link us to our environment and cognitively function in it.

Working memory, in the form of long-term working memory, permits large amounts of information from long-term memory to be used appropriately to organize our interaction with the environment. Thus, readers of this paper can transfer immense amounts of information stored in long-term memory to working memory in order to allow the very complicated squiggles that constitute this page to be organized and interpreted. In that sense, working memory (or long-term working memory) provides a link between long-term memory and the environment.

The environment organizing and linking principle also applies to evolution by natural selection. The epigenetic system, through its interaction with the genetic system, is centrally involved. The interaction of the genetic and epigenetic systems not only involves the transmission of information from the environment to the genetic code, the concern of the narrow limits of change principle discussed above, but more importantly, information transmission from the genetic code that permits an organism to function in its environment. Information transmitted from the genetic code is the concern of the environmental organizing and linking principle. The genetic system, the code in the basic DNA sequence of bases (genotype), incorporates the central information to be expressed indicating which proteins are to be manufactured. It encodes information essential for determining a phenotype (physical and physiological characteristics). In contrast, the epigenetic system contains mechanisms that act outside of or in addition to the basic DNA sequence, and is ultimately responsible for the expression of the information contained in DNA. Any activity subsequent to DNA coding is defined as part of the epigenetic system. Thus, the epigenetic system transmits an interpretation of the information in DNA. It communicates phenotypes and enables the variety of phenotypes to be expressed from the genotype. The epigenetic system transmits information from the information store during the production of proteins required for survival in a particular environment.

It follows that the epigenetic system has a dual purpose: as a response system responding to changes outside the DNA strand and as a transmission system directing

changes in the interpretation of the DNA strand. This dual function mirrors the dual function of working memory that must both handle environmental information and assess its consequences for long-term memory on the one hand and use the information contained in long-term memory to interact with the environment on the other hand. Similarly, the epigenetic system must handle environmental input and determine its consequences for the genome, and use the information in the genome to interact with the environment. Thus, the function of both working memory and the epigenetic system is to act as an intermediary between the information store and the environment.

As is the case for human cognition, large new changes to a genome via the randomness as genesis principle are not possible because there is no central executive directing those changes. Random generation followed by tests of effectiveness act as a substitute for a central executive. Once this process has organized the bases of a genome, that ordered information can be reorganized and linked to the environment. There are no limits to the amount of genetic information with which the environment organizing and linking principle can deal. Whereas successful changes to a genome by mutation or during sexual recombination are always very small, huge amounts of genetic material previously organized via the borrowing or randomness as genesis principle can be marshaled to express particular phenotypes. That marshalling is carried out by the epigenetic system.

A primary action of the epigenetic system is to have a gene activated or silenced. If a gene is activated, a sequence of biochemical reactions occurs to produce the protein product of the gene. All the steps involved in protein synthesis belong to the epigenetic system. The initial step of protein production is transcribing the activated DNA code into an RNA molecule. During this first step, the initial RNA code is rewritten into a messenger RNA by splicing the coding sections. It is at this point that alternative splicing can occur (see the borrowing and reorganizing principle above). During this gene expression, interactions between the DNA code and the environment first occur and these interactions are characteristic of the epigenetic system.

The importance of the epigenetic system in providing a link between the DNA based genetic code and the environment, can be seen simply by considering cell structures. Whatever the genetic makeup of an individual, each of its cells contains identical DNA. Thus, for example, while a cell of an individual's liver contains identical DNA to a cell of the individual's kidney, the two cells are, of course, vastly different in structure and function. Those differences cannot just be due to genetic factors because the nuclei of both cells contain the same genetic codes. The differences are due to the interaction of genetic codes with environmental factors. That interaction is determined by the epigenetic system that can take large amounts of previously organized genetic information and link it with the environment.

Differences in cell structure and function occur because only some genes are activated and thus expressed. In other words, some genes are turned on or off by on/off switches. The activated genes are those whose protein products are required by the particular cell at that time. The requirements of cells depend on the environment of the cells at a specific time, for example, their location in the organism, their stage of development or sudden environmental changes. Thus, protein is produced by DNA in response to a signal outside the DNA.

Most genes (66% or more) are not required by cells and so are "silenced" (completely switched off) by the epigenetic system. When genes are silenced, there is no activation, because even a small amount of unwanted product would disrupt the basic regulating mechanism of the cell. Gene silencing occurs via changes in chromatin

structure (Turner, 2001) as outlined previously. Environmental factors in turn can cause alterations in chromatin structure.

In some cases, gene switching is brought about by the protein products of particular genes (Turner, 2001). These proteins can trigger a chain of events in which the product protein activates a different gene, producing its product, which in turn triggers another gene and so on. In gene activation, both under the control of chromatin and under the control of protein produced by other genes, DNA is responding to outside signals. The DNA is therefore under the control of the epigenetic system that determines whether and which protein will be produced.

This process seems directly analogous to environmental factors determining which schemas in long-term memory are triggered. Most of the many schemas in long-term memory are inactive until a suitable environmental trigger becomes available. Similarly, environmental stimuli can initiate multiple responses from information in long-term memory. This action is comparable to a single gene, under the control of the epigenetic system, producing a number of different proteins in response to varying needs. It is an action brought about by the epigenetic system in genetics and working memory in cognition.

The environmental organizing and linking principle provides the ultimate justification for a natural information processing system. The information store, its creation via the borrowing and reorganizing, randomness as genesis and narrow limits of change principles all are required in order to permit a system that can function in a natural environment. Working memory in cognition and the epigenetic system in biology provide a link between the environment and the information store allowing the environment to determine which information from the information store is to be used and so determining functioning appropriate to the environment. Thus, the environmental organizing and linking principle allows the use of stored information to guide the actions of an entity in its natural environment.

Implications and applications

The above principles describe a system that potentially can function in a natural environment. When formulated in this manner, we believe that system accurately describes evolution by natural selection and more importantly for our purpose, can be extended to human cognition. If this formulation accurately represents human cognition, there are implications that flow for the nature of human cognition and for applications in areas such as education and the presentation of information.

Thought, problem solving, decision making and planning

It may be argued that the very essence of human cognition, our ability to think, solve problems, make decisions and plan is missing from the current theory. If so, that would render the theory catastrophically deficient as a theory of human cognition. In this section we indicate how the principles can account for these critical human cognitive activities.

Knowledge associated with the use of general problem solving strategies is biologically primary knowledge. There are no teachable/learnable general problem solving strategies available to us because we have evolved to acquire such strategies as primary knowledge. We cannot teach people how to use a means-ends strategy because all normal humans automatically use the strategy without tuition. While biologically primary knowledge is presumably stored in an information store, we do not consciously

acquire primary knowledge using the natural information principles described above. For example, the concept of a working memory that is limited in capacity when dealing with novel information but that has no limitations when dealing with organized information from long-term memory has no place when dealing with evolutionary primary knowledge.

While the processes of thinking and problem solving constitute primary knowledge, when these processes are applied to secondary knowledge, the principles of natural information processes become relevant. Using a means-ends strategy may not be teachable because we learn to use it automatically as part of our biological primary knowledge. Applying that strategy to, for example, a novel mathematical problem immediately brings the principles of natural information processing systems into play because most mathematical knowledge is biologically secondary. We may not need to consciously process the mechanisms of means-ends analysis in working memory because the mechanisms of means-ends analysis have been acquired as primary knowledge, but we do need to process the secondary information of novel mathematics in working memory.

When dealing with biologically secondary information, the inter-relation between the borrowing and reorganizing, randomness as genesis and environmental organizing and linking principles can describe how higher level cognitive processes function. When we think, in the first instance information from long-term memory becomes active in working memory using the environmental organizing and linking principle. At this point, nothing new has been created because we are merely bringing previously acquired information into working memory. Thinking requires one or other or both of two additional processes. We may reorganize the information in the same way as information is reorganized during sexual reproduction, alternative splicing or transposition using the borrowing and reorganizing principle. If we have not been provided with additional information indicating how the previous information should be reorganized, then just as occurs in the case of sexual reproduction, we must randomly reorganize the information prior to testing it for effectiveness. Does the new, reorganized information meet our goals as determined by the environment? If it does, we can use the new reorganized information by storing it in long-term memory for later use either in its current form or to be further reorganized during thought.

Most thought, just as most variation in genetics, can be hypothesized to occur by this process of reorganization. On less frequent occasions, entirely new information is generated. When information is transferred from long-term to working memory using the environmental organizing and linking principle, rather than reorganizing it, the information may be randomly altered in the same way as mutation alters the information in DNA. Such random alteration of information transferred from the long-term store is also part of the thought process. As is the case for reorganization, the consequences of randomly altering information cannot be known prior to the occurrence of the alteration. The thought process requires us to randomly alter the information and then, as occurs in the case of mutation, test the alteration for effectiveness with effective alterations being available for storage in long-term memory.

We suggest that these interactions between the borrowing and reorganizing, randomness as genesis and environmental organizing and linking principles provide the basis for higher order processes. When problem solving, we either reorganize previous information and test it for effectiveness as occurs during sexual reproduction or randomly generate new information as occurs during mutation that also must be tested for effectiveness. Failing knowledge in long-term memory, random generation seems

unavoidable. Consider a problem solver attempting to solve a problem using analogical problem solving (e.g., Gick and Holyoak, 1980; 1983). If we do not have knowledge either from our own or the long-term memory of someone else, we have no way of knowing whether a potential analogue is going to be useful and so must randomly choose a particular source analogue as part of the problem solving process. If we are able to solve the target problem using the source analogue, the test part of random generate and test has succeeded and the new information can be stored. Frequently, attempts at analogical problem solving may fail because either the correct analogue is not used or is used inappropriately – if we do not have information about how to use an analogue that process too requires a random generation and test procedure. We suggest that these processes may indicate why reasoning by analogy can be so difficult (Gick and Holyoak, 1980; 1983). It should also be noted that reasoning by analogy requires simultaneous manipulation of information concerning two or more problems that is likely to impose a heavy working memory load.

An identical process provides a viable sub-stratum for decision making. All decisions can be assumed to depend on a combination of previous knowledge where that knowledge is available and random generation and test to the extent that it is not available. The manner in which knowledge is used, including faulty knowledge based on emotions or other factors, leads to the well-known cognitive illusions based on decision making (Kahneman and Tversky, 1996).

Planning is a characteristic activity of human behavior. It can be treated as a particular example of thought and accordingly, can be analyzed using interactions between the borrowing and reorganizing, randomness as genesis and environmental organizing and linking principles. We learn to use particular plans and particular planning procedures. As is the case with other cognitive activities, most of our plans are obtained from our own or someone else's long-term memory. They may be reorganized to fit a particular situation but if so, they require a random generation and test process to determine whether the reorganized plan is effective. Entirely new plans can be created by randomly generating and testing novel procedures.

The theory outlined here does not eliminate thought but rather, attempts to explain it in terms of the interactions among the borrowing and reorganizing, randomness as genesis and environmental organizing and linking principles. Whether the theory is valid will depend, at least in some respects, on rational rather than empirical issues. For example, while the randomness as genesis principle may be contentious in human cognition, we cannot directly test whether that principle rather than an alternative must be invoked in the absence of relevant knowledge by an individual, because we are unable to generate any usable alternative. When relevant knowledge is unavailable, including knowledge that would allow us to generalize to similar situations, there seems to be no alternative to random generate and test against which we could design an empirical test. There seems to be no such alternative either in natural or artificial information processing systems. In contrast, we do know that random generation and test is used during evolution by natural selection. With respect to empirical issues, as noted above, when problem solvers solve difficult, multi-move problems, they will often arrive at more dead-ends than correct moves. Random generate and test can explain many dead-ends that also would need to be explained by an alternative.

Cognitive load theory

Cognitive load theory (e.g., Clark, Nguyen and Sweller, 2006; Leahy and Sweller, 2005; Paas, Renkl and Sweller, 2003; Sweller, 1988; 2003; Sweller, Chandler, Tierney and Cooper, 1990; Sweller, Mawer and Ward, 1983; van Merriënboer and Sweller, 2005) is an instructional theory that uses versions of the cognitive architecture described here to generate instructional procedures. In that sense, the current theory has instructional applications. As is the case with all instructional applications, they are only relevant to biologically secondary knowledge. Some of the instructional applications differ markedly from some commonly used recommendations in the field of instructional design. Summary details of the specific instructional applications may be found elsewhere (e.g., Sweller, 2003, 2004) and so will not be presented here. General consequences of the use by cognitive load theory of the cognitive processes indicated in this paper will be discussed next.

Cognitive load theory assumes that the primary aim of instruction is to efficiently build a large information store in long-term memory in order to permit the environmental organizing and linking principle through long-term working memory to be used. The narrow limits of change principle through a limited working memory provides a major impediment and so instructional techniques need to be devised that permit learners to avoid that impediment. Because the borrowing and reorganizing principle provides the best way of building the information store in long-term memory, cognitive load theory places a very heavy emphasis on various techniques for directly presenting information to learners. All of the instructional effects generated by the theory have involved various ways of reducing unnecessary working memory load during the presentation of auditory and visual information in order to assist in the construction of schemas in long-term memory.

In contrast, much current instructional psychology places a considerable emphasis on encouraging learners to generate their own knowledge rather than providing direct, explicit instruction. That emphasis has been pre-eminent since Bruner's (1961) formulation of "discovery learning" according to which learning is enhanced if learners discover procedures and concepts as a substitute for explicit instruction. More recent approaches emphasize "constructivist teaching" procedures or "inquiry learning" but are indistinguishable from discovery learning (Kirschner, Sweller and Clark, 2006). As far as we are aware, at no stage during the decades of this movement has there been any attempt to analyze the cognitive mechanisms of discovery. While learners will assimilate biologically primary information without direct instruction there is no body of evidence of which we are aware that biologically secondary information can similarly be assimilated readily without explicit instruction. Cognitive load theory, by applying natural information processing principles to secondary knowledge, can provide the following analysis.

Inquiry based learning places its emphasis on the randomness as genesis principle rather than the borrowing and reorganizing principle. Learners, faced with learning new material, are in effect being asked to solve a novel problem. Since, by definition, they are novices who do not have the required information in long-term memory and have been prevented from obtaining the information from the long-term memories of those who have preceded them, they must randomly generate the required information themselves and test it for effectiveness. If the theory outlined in this paper is valid, that is equivalent to having an organism or complex structure spring from a single, massive mutation. Neither the epigenetic system nor human working memory is equipped to handle such a large amount of novel information from the environment at once.

Because of the impossibility of learners discovering large amounts of information that took civilizations thousands of years to develop, the concept of “guided discovery” or “scaffolding tools” (de Jong, 2006) became current. By guiding learners in discovery, more use of the borrowing and reorganizing principle is made but nevertheless, whatever is left to discover still has the same problems that are associated with the randomness as genesis principle. Based on the current theory, inquiry-based learning should not prove effective compared to direct instructional guidance.

Given the above analysis, we can predict that empirical evidence for inquiry-based learning should be sparse, at best. In fact, despite almost half a century of advocacy, there is no body of coherent literature using randomized controlled experiments demonstrating the advantages of inquiry-based learning. In contrast, the worked example effect, an effect generated by cognitive load theory, consistently has demonstrated that presenting novices with worked examples results in more learning than presenting them with problems to solve (Carroll, 1994; Cooper and Sweller, 1987; Miller, Lehman and Koedinger, 1999; Paas, 1992; Paas and van Gog, 2006; Paas and van Merriënboer, 1994; Pillay, 1994; Quilici and Mayer, 1996; Reisslein, Atkinson, Seeling and Reisslein, 2006; Sweller and Cooper, 1985; Trafton and Reiser, 1993; van Gog, Paas and van Merriënboer, 2006). Use of the randomness as genesis principle may be unavoidable when we do not have access to an organized knowledge base either in our own or another person’s long-term memory. According to the current theory, if knowledge is available, we should use the borrowing and reorganizing principle not the randomness as genesis principle.

Conclusions

The last few decades have seen an increasing emphasis on an analogy between biological evolution and the acquisition of human knowledge. There is increasing evidence that the analogy potentially may provide a defining framework for the evolution of human culture. In this paper, we have attempted to advance this process by including human cognition as part of the analogy. For biologically secondary knowledge, we have equated DNA in a cell nucleus with long-term memory, reproduction with learning from other people, random mutation with random generate and test during problem solving, the epigenetic system when dealing with a novel environment with working memory when dealing with novel information, and the epigenetic system when managing genomic information with long-term working memory (Table 1).

The current theory has been formulated on the assumption that human cognition, as part of the natural world, shares a common base with other natural information processing systems such as evolution by natural selection, rather than being a structurally unique construct. Both systems create novel information, organize it, remember it for subsequent use, and disseminate it over space and time. By considering both cognition and evolution by natural selection as natural information processing systems, processes of human cognition can be manifested that otherwise might remain hidden. Those processes have implications for both how we view our place in the natural world and for how we present information to those who require it.

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