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35 Evolutionary Bases for Cognition and Instruction

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Human cognitive architecture has evolved according to the principles of biological evolution, just as all human structures and functions have evolved according to the same principles. Not only have biological evolutionary principles governed the evolution of human cognition, the underlying logic of biological evolution and human cognition may be analogous (Sweller & Sweller, 2006). Both are natural information processing systems that function in a similar manner. Human cognitive architecture may recapitulate evolution by natural selection.

In order to function, a natural information processing system requires several structures and processes: It requires; (1) a store of information; (2) a process for rapidly acquiring that information from other stores; (3) a process for generating new information that cannot be obtained from other stores; (4) mechanisms to ensure that any new information generated does not interfere with useful, previously stored information; and (5) a procedure to use elements of stored information appropriately when it is needed. The last procedure, an ability to use stored information appropriately, provides a justification for the entire system. Appropriate use of stored information will allow a system to function in its environment. Without this ability, the system will be dysfunctional. In the next section, each of these structures and processes will be discussed in detail with respect to their relevance to evolution by natural selection and human cognition.

Human Cognitive Architecture

Human cognition can be described in terms of an information processing system. Evolution by natural selection, while normally considered as a biological theory, also can be described as an information processing system. Furthermore, the systems used to describe human cognition and evolution by natural selection are closely analogous. Both systems can be described using five basic principles.

The Information Store Principle

To function in most natural environments, natural information processing systems require very large stores of information. The more complex and variable the environment, the larger the required store of information. In the case of evolution by natural selection, a genome provides the necessary information store. While there is no agreed on procedure for measuring the size of genomes (Portin, 2002; Stotz & Griffiths, 2004), all measures considered such as number of base pairs or number of genes indicate that a viable genome consists of a large amount of information. That information allows a genome to survive and reproduce in what is frequently a variable environment.

In the case of human cognition, long-term memory provides a large, permanent information store. The central importance of long-term memory to all facets of cognition only has become apparent over the last few decades. Long-term memory does not simply consist of elements of unrelated, rote learned information with no or minimal consequences for our cognitive processes. Rather, it consists of a large number of complex, related elements of information that can determine much of our activity, including sophisticated problem solving.

Work by De Groot studying experts in the game of chess provided the major impetus for our initial understanding of the importance of long-term memory to problem solving skill (De Groot, 1965; De Groot & Gobet, 1996). De Groot found that the differences in skill between weekend players and chess masters could not be explained by a differential ability to consider a greater number of potential moves. Chess masters do not consider more potential moves than weekend players. The only difference De Groot could find between different levels of chess skill was in memory of board configurations taken from real games. Both masters and weekend players were shown a board configuration taken from a real game for 5 seconds before having it removed and being asked to reproduce the configuration. Chess masters could correctly replace about 70% of the pieces while weekend players only could replace about 30%. Chase and Simon (1973) replicated these results and in addition found that for random board configurations, there was no difference between masters and weekend players. Both were able to reproduce only about 30% of briefly seen, randomly placed board configurations. Chess masters were only superior when reproducing configurations taken from real games.

It takes a minimum of about 10 years of practice to become a chess grand master (Ericsson & Charness, 1994). We now know the cognitive changes that occur during this period. Chess masters are not acquiring complex, sophisticated, general problem solving strategies. Rather, they are learning to recognise tens of thousands of board configurations and the best moves associated with each configuration. This domain-specific knowledge held in long-term memory provides the basis of skilled performance in all areas, including areas relevant to education. Results similar to those obtained by De Groot have been obtained in a large number of educationally relevant areas (Chiesi, Spilich, & Voss, 1979; Egan & Schwartz, 1979; Jeffries, Turner, Polson, & Atwood, 1981; Sweller & Cooper, 1985).

The Borrowing and Reorganising Principle

How are the large amounts of information specified by the information store principle acquired? In the case of a genome, the process is well-known. Apart from mutations (see next section) all information in a genome is borrowed from ancestor genomes. In the case of asexual reproduction, off-spring genomes are identical to ancestor genomes apart from mutations. In the case of sexual reproduction, off-spring genomes are a combination of the two parent genomes, ensuring that off-spring are necessarily different from parents, and apart from identical siblings, different from each other. Sexual reproduction provides an example of the borrowing and reorganising principle with information borrowed from ancestors but reorganised when an individual is created.

Human cognition also uses the borrowing and reorganising principle to rapidly obtain information for the information store. We imitate what other people do (Bandura, 1986) read what they write and listen to what they say. In this way, we obtain information from other people's long-term memories. That information is combined with our previous knowledge to create new knowledge. In this manner, information can be accumulated in long-term memory relatively rapidly.

The Randomness as Genesis Principle

While the vast majority of information held in an information store is obtained from other stores via the borrowing and reorganising principle, that information must be created in the first instance. The manner in which evolution by natural selection creates novel information is well known. All genetic variation ultimately can be sourced to random mutations. The general process can be described as random generate and test. Random mutations are tested for adaptivity with adaptive mutations retained and non-adaptive mutations jettisoned. This process is the ultimate source of all the considerable creativity demonstrated by evolution by natural selection.

Problem solving plays the same role in human cognition. Ultimately, random generate and test provides the engine of novelty in human cognitive architecture. While a variety of problem solving procedures such as means-ends analysis (Newell & Simon, 1972) or analogical problem solving (Gick & Holyoak, 1980) are available, at some point, all of them rely on random generate and test to generate novelty. Accordingly, this principle is essential to analyses of human creativity (Sweller, 2009). While most of the knowledge held in human long-term memory is acquired from the long-term memories of other people as specified by the borrowing and reorganising principle, all of that knowledge had to be created in the first instance using a random generate and test process. Any individual can only create a small part of their knowledge base using the randomness as genesis principle but humans as a species have ultimately created their entire knowledge base in this manner.

The Narrow Limits of Change Principle

The randomness as genesis principle has structural consequences. If novel information must be randomly generated, the number of elements of information from which the novel information is generated must be restricted.

For example, using the logic of permutations, there are 3! = 6 permutations of 3 elements. There are 10! = 3,628,800 permutations of 10 elements. It may be feasible to generate and test 6 permutations. It may be unrealistic to generate and test 3,628,800 permutations.

The human cognitive system reduces the number of novel combinations of elements with which it must deal by processing novel information using a limited capacity, limited duration working memory. When dealing with novel information, our working memory has a capacity of no more than about 4 items (Cowan, 2001; Miller, 1956) and a duration of no more than about 20 seconds without rehearsal (Peterson & Peterson, 1959). These limits ensure that the number of combinations that must be tested when dealing with novel information is realistic. Testing for an appropriate way of combining about 4 items is likely to be possible. Testing how 10 or more items should be combined may be impossible.

The epigenetic system in evolutionary biology acts as an anologue to working memory in human cognition. It is capable of increasing or decreasing the rate of mutations at various points in a genome (Jablonka & Lamb, 2005; West-Eberhard, 2003) just as working memory determines which problems will be selected for consideration. In both cases, random generation and test as determined by the randomness as genesis principle is affected, indeed constrained, by the narrow limits of change principle. The limitations of working memory ensure that large, rapid changes to long-term memory that could destroy the effectiveness of long-term memory do not occur. Rapid changes to a genome do not occur for the same reason. A large change to a genome is likely to be maladaptive.

The Environmental Organising and Linking Principle

This principle provides a justification of the previous principles. It ensures that the information store is used appropriately in its environment. In the case of biological evolution, the epigenetic system again is the critical system. In this case, it deals with organised information held in a genome rather than the novel, external information dealt with by the narrow limits of change principle. The epigenetic system determines which genes are turned on or off. Some genes are activated while others are silenced. The consequences can be seen clearly by considering different cells with an identical genetic code. For example, phenotypically, a liver cell bears little relation to a skin cell. Yet for any given individual, the DNA found in the nucleus of a skin cell is identical to the DNA found in the nucleus of a liver cell. The differences between the cells cannot be due to genetic differences. They are due to epigenetic differences with some genes activated and others silenced. Furthermore, because in this case, we are dealing with organised information, there are no known limits to the amount of information that can be controlled by the epigenetic system. Huge amounts of information can be affected by the epigenetic system with large consequences for phenotypical characteristics.

Working memory plays the same role in cognition as the epigenetic system plays in genetics. Working memory determines which information from long-term memory will be used and which information will be ignored. As is the case for the epigenetic system, there are no known limits when working memory deals with information from the information store (long-term memory). The capacity and duration limits associated with working memory when it deals with novel information from the environment disappear when working memory deals with organised information from long-term memory. Large amounts of organised information from long-term memory can be brought into working memory for unlimited amounts of time (Ericsson & Kintsch, 1995). That information determines how we view the world and how we react to it.

Biologically Primary and Biologically Secondary Knowledge

The principles outlined above constitute a human cognitive architecture. It is an architecture that applies particularly to knowledge dealt with in educational institutions. There are two important categories of knowledge (Geary, 2012): Biologically primary and biologically secondary knowledge. Primary knowledge is knowledge we have evolved to acquire over many generations. Learning to listen to and speak a first language, recognise faces, engage in routine social relations, or use a general problem solving strategy provide examples. We do not need to be explicitly taught biologically primary knowledge. Membership of any functioning society will result in us automatically acquiring biologically primary knowledge. For this reason, the curriculum documents of educational institutions usually do not refer to biologically primary knowledge.

In contrast to biologically primary knowledge, we have not specifically evolved to acquire biologically secondary knowledge. It is knowledge that we need for cultural reasons. Learning to read and write provide examples that can be contrasted to learning to listen and speak. While we do not need to be explicitly taught to listen and speak our first language, unless we are explicitly taught to read and write, most members of society will not acquire the necessary skills. Simple immersion in a reading and writing society will not guarantee that an individual will learn to read and write. In contrast, immersion in a listening/speaking society guarantees all but disabled people will learn to listen and speak.

Educational institutions were established precisely in order to ensure that necessary biologically secondary skills are acquired. Without formal education, most people will not acquire the skills taught in schools and other educational institutions.

The cognitive architecture outlined above applies to biologically secondary, not biologically primary skills. For example, the limitations of working memory outlined above, apply to biologically secondary not biologically primary knowledge. We can process enormous amounts of biologically primary knowledge in working memory without conscious effort. As another example, we do not use random generate and test or engage in problem solving when dealing with biologically primary knowledge because we have evolved to acquire biologically primary knowledge. We do not need to search for problem solving moves when dealing with primary knowledge because we have evolved to make the appropriate moves. In contrast, we do need to engage in random generate and test when dealing with secondary knowledge. While the process of random generate and test is almost certainly biologically primary in that we do not need to be taught the procedure, we apply it to biologically secondary information and may need to have indicated to us which secondary knowledge is amenable to a random generate and test procedure. In other words, we may use biologically primary information to assist us in acquiring biologically secondary information (Paas & Sweller, in press).

Cognitive Load Theory

Cognitive load theory uses the above architecture to assist in designing instruction that reduces working memory load and facilitates the acquisition of domain-specific information stored in long-term memory (Sweller, 2011; Sweller, Ayres, & Kalyuga, 2011). The theory has been used to generate a variety of effects where an effect is based on a randomised, controlled experiment in which an instructional procedure generated by cognitive load theory results in superior outcomes to a more traditional procedure. Each experimental effect, in turn, provides us with a new or different procedure that can be used in instructional contexts. Many such procedures have been identified and tested using randomised, controlled experiments (Sweller, Ayres, & Kalyuga, 2011). The success of cognitive load theory in generating new instructional procedures provides some assurance concerning the validity of the cognitive architecture used to generate them. That cognitive architecture has been discussed in this chapter.

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