Educ Psychol Rev (2009) 21:11–19
DOI 10.1007/s10648-008-9091-6

REVIEW ARTICLE

Cognitive Bases of Human Creativity

John Sweller

Published online: 29 November 2008

Abstract Cognitive load theory has been concerned primarily with techniques that will facilitate the acquisition by students of knowledge previously generated by others and deemed to be important by society. The initial generation of that knowledge, a creative process, has been largely ignored. The recent expansion of cognitive load theory's cognitive architectural base to incorporate evolutionary biological principles has opened the possibility of using the theory to consider the generation of knowledge as well as its transmission. It has been suggested that the logical base that underlies evolution by natural selection also underlies human cognitive architecture. The purpose of evolutionary theory is to explain the creation of new biological entities and processes. If human cognitive architecture is organized around the same principles, it should analogically be possible to explain knowledge generation. This paper will outline the relevant theoretical machinery, indicate data that support the theory, and indicate instructional procedures that, based on the theory, should facilitate creativity.

Keywords Cognitive load theory · Creativity · Human cognitive architecture · Evolutionary psychology · Instructional processes

Human creativity has been of interest to psychologists and educationists for generations (e.g., Guilford 1959; Torrance 1966). That interest has led to neither substantial advances in our understanding of creative processes nor to theory-based techniques for enhancing human creativity. We do not, for example, have educational techniques intended to enhance human creativity that are supported by a body of empirical research using randomized, controlled studies demonstrating the effectiveness of the techniques. A lack of connectivity between research into creativity and our rapidly advancing knowledge of human cognitive architecture may partly explain the failure to advance knowledge in this area. In this paper, I suggest that re-conceptualizing creativity within a cognitive architectural framework has the potential to both increase our knowledge of the process and provide avenues for research into enhancing human creativity.

J. Sweller (✉)
School of Education, University of New South Wales, Sydney, NSW 2052, Australia
e-mail: j.sweller@unsw.edu.au

An Evolutionary Psychological Base for Human Cognitive Architecture

Humans view themselves as being creative, and a simple observation of the progress of civilization over the last few thousand years attests to the validity of this view. But, there is one piece of baggage almost invariably associated with the assumption of human creativity. Outside of theological considerations, there is a sometimes explicit, sometimes implicit assumption of uniqueness. We tend to assume that human creativity is unique on earth. It is a peculiar assumption. We have expended enormous effort and resources for over a century creating one of our most important scientific theories, evolution by natural selection, specifically intended to explain how life on earth was created. As a consequence, in evolution by natural selection, we have an unambiguously creative force that, on almost any measure, vastly exceeds human creativity. Indeed, evolution by natural selection not only created humans, it presumably also created human creativity.

The creative mechanisms of evolution by natural selection are very well known. Because those mechanisms gave rise to human creativity, it may be reasonable to assume that those same mechanisms are required when considering human creativity. It may be plausible to assume that the human cognitive architecture that evolved via the mechanisms of evolution by natural selection requires the same mechanisms with the same logical base as its creative source. If so, evolution by natural selection may be used analogically when considering human cognitive architecture and its creative potential. Before doing so, I will suggest which categories of knowledge are important when analyzing those aspects of human creativity that are relevant to current concerns.

Biologically Primary and Biologically Secondary Knowledge

Knowledge can be divided into many categories, but there are two that are critical when considering human cognitive architecture: biologically primary and biologically secondary knowledge (Geary 2007). Biologically primary knowledge is knowledge that we have evolved to acquire over many thousands of generations. Learning to listen and speak, recognize faces, or use general problem-solving techniques provide examples. We acquire these skills easily, without conscious effort and without explicit instruction because we have evolved to acquire the relevant knowledge. It can be acquired simply by immersion in a functioning society. Each skill is independent of other biologically primary skills and is likely to have evolved independently.

We also have evolved to acquire biologically secondary knowledge, but it is quite different from biologically primary knowledge. Secondary knowledge is any knowledge that has become culturally important relatively recently and for which insufficient time has elapsed for us to have evolved modular structures to handle those categories of information. Unlike biologically primary knowledge, we have not evolved to acquire particular categories of biologically secondary knowledge. Rather, the secondary system is designed to acquire any knowledge that we might need, and so, biologically secondary knowledge tends to be acquired using procedures with several common characteristics. For example, whereas biologically primary knowledge can be acquired effortlessly without conscious thought, biologically secondary knowledge requires conscious effort. It is assisted by explicit instruction because information on acquisition techniques has not been biologically programmed as is the case for biologically primary knowledge. Explicit instruction can act as a substitute for the biological programming available when obtaining information that we have evolved to acquire.

Schools and educational institutions were invented in order to help people acquire the biologically secondary knowledge required by modern societies. We have not evolved to acquire the many branches of knowledge taught in educational and training institutions effortlessly and unconsciously because they have only been required recently in human history. The cognitive architecture described next applies to the biologically secondary knowledge that is the subject of interest in educational institutions. While the acquisition of that knowledge depends on the prior acquisition of biologically primary knowledge and will result in learning-disabled students if the relevant primary knowledge has not been acquired, the procedures used to acquire secondary knowledge are all similar irrespective of the characteristics of that knowledge and very different from the many procedures required for the acquisition of primary knowledge.

Human Cognitive Architecture

The human cognitive system has evolved to process information in a manner similar to the manner in which evolution by natural selection processes information (Sweller 2003, 2004; J. Sweller and Sweller 2006). Both are examples of natural information processing systems. Accordingly, we can use the well-known procedures of evolutionary biology to provide us with a guide to human cognition. While human cognition is frequently analyzed as an information processing system, evolutionary biology normally tends not to be thought of in information-processing terms. The five basic principles outlined below provide one template for analogically considering evolution by natural selection and human cognition.

Information store principle A massive store of information is central to the functioning of both evolutionary biology and human cognition. A genome provides that information store in the case of evolution by natural selection while long-term memory provides a similar function in the case of human cognition. De Groot's (1965) work on the sources of expertise in the game of chess provides evidence for the critical importance of long-term memory in human cognition, including problem solving and thinking.

Borrowing and reorganizing principle The bulk of information in the information store is obtained by borrowing prior to reorganization from other information stores. Biological evolution uses sexual reproduction for this purpose with all genomic information of offspring (apart from mutations—see next principle) obtained from parents using a procedure that necessitates reorganization. That reorganization ensures that offspring cannot be identical to a parent. Similarly, most of the information in long-term memory is obtained from other people by imitation, by listening to what others say, or by reading what they write. Before being stored, information is transformed and re-organized by previous information held in long-term memory. The various instructional techniques devised under a cognitive load theory umbrella are all predicated on the assumption that information presented to be imitated or presented in spoken or written form is essential to acquiring biologically secondary knowledge (e.g., Clark *et al.* 2006; Sweller 2003, 2004).

Randomness as genesis principle In evolutionary biology, this principle provides the engine of creativity. All variation between genomes ultimately can be sourced to random mutation. It must be emphasized that the procedure is not a simple random mutation procedure but rather a random generation and test for effectiveness procedure. Without a test for effectiveness, random mutation could not function as a generator of creativity. Neither could it function without the other principles listed here. Without an appropriate information store, random generate and test is highly unlikely to be successful. It is suggested that all human creativity is similarly critically dependent on a random generation and test of effectiveness process during problem solving. Nevertheless, as is the case for evolutionary biology, random generation and test is always constrained by the information store, in this case, a knowledge base. We may reject many possible problem-solving moves because we know those moves will be ineffective. Despite rejecting many moves based on knowledge, when faced with a novel problem, we may have several possible moves that we cannot distinguish between in terms of effectiveness. We may have no choice but to randomly choose a move and test it for effectiveness, and that process may be a creativity generator.

Narrow limits of change principle If random generation is intrinsic to the creation of novel information as suggested by the randomness as genesis principle, there are structural implications. Structures are required capable of limiting the explosive growth in the potential number of possible novel entities that can be generated. The issue can be seen clearly by a simple numerical example. When dealing with three entities, there are $3!=6$ permutations. When dealing with ten entities, there are $10!=3,628,800$ permutations. An information processing system may be able to successfully generate and test six permutations but may find it difficult to successfully generate and test over 3.5 million permutations. Human cognitive architecture allocates the generate and test process to working memory. The well-known capacity (Miller 1956) and duration (Peterson and Peterson 1959) limits of working memory may exist, at least in part, because of the requirements of the narrow limits of change principle.

Working memory acts as an intermediary between long-term memory and the environment. The epigenetic system plays the same intermediary role between the information store and the external environment as does working memory (Sweller and Sweller 2006).

Environmental organizing and linking principle The aim of the previous four principles is to permit a natural information processing system to function in its environment. The environmental organizing and linking principle is the ultimate principle that allows the system to meet this requirement. In human cognition, this principle links the environment to long-term memory by linking working memory to long-term memory. In the process, the characteristics of working memory are dramatically altered. As indicated by the narrow limits of change principle, when working memory must deal with novel information from the environment, it is severely limited in duration and capacity. In contrast, when working memory deals with information from long-term memory, capacity and duration limits are vastly expanded (Ericsson and Kintsch 1995). Indeed, there may be no working memory limits when dealing with information from long-term memory. Huge amounts of information can be easily and readily marshalled from long-term memory for use by working memory to generate actions required by a large number of complex environments. Similarly, in evolutionary biology, massive amounts of genomic information can be used by the epigenetic system to govern the protein synthesis required by a particular environment. Thus, the environmental organizing and linking principle provides the ultimate justification for a natural information processing system.

Creativity

Based on this architecture, a natural information processing system only is likely to be able to function if it has acquired the large amounts of information required by its environment. The borrowing and reorganizing principle explains how most of this information is acquired but only partly explains how it is created. Some novel information is created during any process of reorganization. Reorganization occurs during sexual reproduction and when information is acquired from another person and combined with current information. This reorganization results in the creation of novelty, but it is novelty created by novel mixes of information that was previously generated. True novelty is created by the randomness as genesis principle, and it is that principle that will be discussed in detail in this section.

The first point to note is that whether or not one agrees with the randomness as genesis principle in human cognition, it is capable of creating novelty. Under evolution by natural selection, it is the ultimate creator of all biological novelty. Without exception, all differences between one biological entity and another can be sourced to mutation. In that sense, the unsurpassed creativity exhibited by evolution by natural selection can be attributed to the randomness as genesis principle. It follows that, if the analogy between evolution by natural selection and human cognition outlined above holds, then at the very least, some aspects of human creativity could be sourced to the same principle. But, is it necessary for human creativity as it is for evolution by natural selection?

Merely observing humans reaching dead ends while solving a difficult problem provides evidence that is likely to convince most that we do, on at least some occasions, use random generate and test when solving problems. Random generate and test can explain dead ends as well as successful problem solving, but the issue is not whether random generate and test can explain some acts of human creativity but whether it must be used to explain all creative acts as is the case for evolutionary biology. Can it not only explain dead ends and some successful novel problem-solving moves but all novel problem-solving moves not generated by knowledge in long-term memory? This hypothesis, of course, can never be confirmed, only disconfirmed. Evidence of a creative problem-solving strategy that did not include random generate and test would both instantly disprove the hypothesis and, indeed, indicate that the analogy between evolutionary biology and human cognition broke down at this point. Such evidence currently is unavailable.

Let us analyze problem solving in more detail. Consider a person choosing problem-solving moves. For most problems, knowledge will be pre-eminent in making the choice. Knowledge is likely to be used to eliminate many moves and so restrict problem-solving choice to just a subset of possible moves. For example, when navigating our way around a physical location such as a university campus or a city, we do not consider all possible paths or roads to go from A to B but rather restrict our choice to directions that previous knowledge informs us are the most likely candidates. Nevertheless, if the location is novel, at some point we are likely to be faced with a situation in which two or more directions are, as far as we can see, just as likely to lead to our goal. There is nothing in long-term memory favoring one move or set of moves over another nor, let us assume, can we readily borrow information from another source such as another person or a map. We have reached a point where the borrowing and reorganizing principle cannot be used. How do we proceed? Random generate and test seems to be the only possibility. We must, either mentally or physically, randomly choose a move and determine what is the outcome of that move. Note that, in the absence of appropriate knowledge, we cannot know the outcome of that move prior to making it. Because the outcome cannot be known prior to a test of its effectiveness, the move must be chosen randomly.

In the absence of knowledge, there appears to be no alternative to random generate and test. Unless an alternative is found, it is reasonable to suggest that the randomness as genesis principle is not only required by evolution by natural selection to explain biological creativity, it may similarly be required for human creativity. Humans are creative while solving problems and, from a given knowledge base, the randomness as genesis principle with its reliance on random generate and test may provide the only available mechanism for generating novel moves. If so, the randomness as genesis principle provides the basis for human creativity.

Facilitating Creativity

The above analysis, if valid, places very clear restrictions on facilitating creativity and explains the failure of previous attempts. Creativity derives from random generate and test that is likely to be a biologically primary skill. As a matter of survival, we must be able to randomly generate and test, and indeed, the skill may have been acquired by our prehuman ancestors.

We have evolved to acquire biologically primary skills, and so these do not usually have to be explicitly taught, but it may be possible to enhance those skills. While we learn to listen to and speak our native language without tuition, that does not mean we cannot improve our language facility. Similarly, it may be possible to encourage people to engage in random generate and test under conditions where they may not normally do so or to an extent greater than usual. If so, procedures to encourage random generate and test may facilitate creativity under limited conditions.

The extent to which random generate and test is used and the types of problem-solving moves that require random generate and test will depend heavily on a knowledge base. An extensive, sophisticated knowledge base will not only reduce the number of problem-solving moves that need to be chosen using the randomness as genesis principle because they are already located in the information store; it will change the types of moves. An extensive knowledge base allows us to randomly generate and test the effectiveness of moves that could not possibly be considered by a person without that knowledge base. If one does not know the properties of vacuums or inert gasses, one cannot invent a light bulb. Accordingly, the first requirement of creativity is an extensive knowledge base, and we know an extensive knowledge base is both teachable and learnable. Such a knowledge base is a requirement for creativity, and it is notable that few if any people demonstrate creativity without first spending long periods of time developing an appropriate knowledge base.

Nevertheless, despite the critical importance of an extensive knowledge base, the current argument suggests that the ultimate source of creativity is the randomness as genesis principle. Intriguingly, as indicated above, while generate and test is probably a biologically primary skill in that it is not generally taught and is not usually part of educational curricula, there may be some aspects that are teachable and that can increase creativity. For example, many mathematics instructors teach “guess and check” as a method of problem solving. In addition, we have known of the effects of “brainstorming” for decades (e.g., Meadow *et al.* 1959; Osborn 1953). The procedure initially was devised by Osborn (1953) as a practical technique with no theoretical base. It placed an emphasis on the generation of a large quantity of novel ideas in a group rather than an individual problem-solving context. Idea generation was associated with a deferral of judgment concerning the effectiveness of problem solutions. It was assumed that, if the quantity of ideas was increased, the quality of the best ideas would also increase.

Despite the lack of a theoretical base, numerous studies have indicated that brainstorming instructions do increase the number of good ideas. Furthermore, it is clear that group problem solving is not required with the number of ideas generated being greater for individual rather than group problem solving (Bouchard and Hare 1970; Dillon *et al.* 1972; Dunnette *et al.* 1963; Taylor *et al.* 1958). Simply asking individuals to generate as many ideas as they can as quickly as they can has a positive effect on the number of good problem solutions. An obvious question is what aspects of human cognition result in brainstorming instructions having a positive effect? The cognitive architecture discussed in this paper provides a theoretical rationale for brainstorming, explains why it is successful, and indicates conditions under which brainstorming might be an effective technique for increasing creativity.

The randomness as genesis principle, as the basic generator of novelty in natural information processing systems, is accordingly the basic generator of novelty in human cognition. This principle can be used to explain the effectiveness of brainstorming. Novelty, according to the randomness as genesis principle, derives from a random generate and test process. Brainstorming requires a rapid generation of random ideas from an extant knowledge base. Encouraging problem solvers to randomly generate a large number of problem-solving moves under conditions where they do not have sufficient knowledge in long-term memory to guide move selection may be an effective means of problem solving leading to creative solutions. Brainstorming may work because it maximizes use of the randomness as genesis principle to generate novel moves.

The Goal-Free Effect

The goal-free effect (Ayres 1993; Bobis *et al.* 1994; Burns and Vollmeyer 2002; Geddes and Stevenson 1997; C. S. Miller *et al.* 1999; Owen and Sweller 1985; Paas *et al.* 2001; Sweller 1988; Sweller and Levine 1982; Sweller *et al.* 1983; Tarmizi and Sweller 1988; Vollmeyer *et al.* 1996) was the first cognitive load effect and may relate to brainstorming and the issues discussed in this paper. Under goal-free problem solving, problem solvers are given a problem to solve without a specific goal. For example, rather than being asked to find a value for angle X in a geometry problem, they are asked to find the values of as many angles as they can. Many experiments over many years have conclusively demonstrated that reducing the specificity of goals in this manner increases learning and problem-solving skills compared to problem solvers presented conventional problems with specific goals.

One of the incidental findings of goal-free problem solving is that problem solvers find values for many more variables in much less time than if they are presented with conventional problems (e.g., Owen and Sweller 1985). Goal-free problem solving may share some characteristics with brainstorming in that both techniques require the generation of as many moves as possible. In the case of brainstorming, problem solvers are asked to withhold judgment of those moves and to simply generate as many moves as possible in the first instance. In the case of goal-free problem solving, problem solvers are not constrained by the need to attempt to reach a goal. Instead, they must generate as many moves as they can without reference to a goal. Other than obeying the rules of the discipline in which they are working, those moves can be generated randomly. In that sense, the moves are generated by the randomness as genesis principle, and the effectiveness of goal-free problem solving may be due to that principle. A random generation of moves, as well as reducing working memory load (e.g., Sweller 1988), may result in the generation of unique moves, thus enhancing creativity.

Conclusion

Work on human creativity in an educational context has not been demonstrably successful with no body of evidence from randomized, controlled experiments able to demonstrate the facilitation of creativity by educational interventions. Indeed, we have had difficulty even defining creativity, let alone encouraging it. Our failure to connect human creativity to our knowledge of human cognitive architecture may, in part, explain our inability to make progress in this area. The current treatment, by linking human creativity to a particular view of human cognitive architecture based on evolutionary biology, provides a conceptualization of creativity that could be potentially productive.

References

Ayres, P. (1993). Why goal-free problems can facilitate learning. *Contemporary Educational Psychology*, *18*, 376–381. doi:10.1006/ceps.1993.1027.

Bobis, J., Sweller, J., & Cooper, M. (1994). Demands imposed on primary-school students by geometric models. *Contemporary Educational Psychology*, *19*, 108–117. doi:10.1006/ceps.1994.1010.

Bouchard, T. J., & Hare, M. (1970). Size, performance and potential in brainstorming groups. *The Journal of Applied Psychology*, *54*, 51–55. doi:10.1037/h0028621.

Burns, B. D., & Vollmeyer, R. (2002). Goal specificity effects on hypothesis testing in problem solving. *The Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, *55A*, 241–261.

Clark, R. C., Nguyen, F., & Sweller, J. (2006). *Efficiency in learning: Evidence-based guidelines to manage cognitive load*. San Francisco: Pfeiffer.

De Groot, A. (1965). *Thought and choice in chess*. The Hague, Netherlands: Mouton (Original work published 1946).

Dillon, P. C., Graham, W. K., & Aidells, A. L. (1972). Brainstorming on a “hot” problem: Effects of training and practice on individual and group performance. *The Journal of Applied Psychology*, *56*, 487–490. doi:10.1037/h0033718.

Dunnette, M. D., Campbell, J., & Jaastad, K. (1963). The effects of group participation on brainstorming effectiveness for two industrial samples. *The Journal of Applied Psychology*, *47*, 10–37. doi:10.1037/h0041308.

Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological Review*, *102*, 211–245. doi:10.1037/0033-295X.102.2.211.

Geary, D. (2007). Educating the evolved mind: Conceptual foundations for an evolutionary educational psychology. In J. S. Carlson, & J. R. Levin (Eds.), *Psychological perspectives on contemporary educational issues* (pp. 1–99). Greenwich, CT: Information Age.

Geddes, B. W., & Stevenson, R. J. (1997). Explicit learning of a dynamic system with a non-salient pattern. *The Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, *50A*, 742–765.

Guilford, J. P. (1959). The three faces of intellect. *The American Psychologist*, *14*, 469–479. doi:10.1037/h0046827.

Meadow, A., Parnes, S., & Reese, H. (1959). Influence of brainstorming instruction and problem sequence on a creative problem solving test. *The Journal of Applied Psychology*, *43*, 413–416. doi:10.1037/h0043917.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63*, 81–97. doi:10.1037/h0043158.

Miller, C. S., Lehman, J. F., & Koedinger, K. R. (1999). Goals and learning in microworlds. *Cognitive Science*, *23*, 305–336.

Osborn, A. (1953). *Applied imagination*. New York: Scribners.

Owen, E., & Sweller, J. (1985). What do students learn while solving mathematics problems? *Journal of Educational Psychology*, *77*, 272–284. doi:10.1037/0022-0663.77.3.272.

Paas, F., Camp, G., & Rikers, R. (2001). Instructional compensation for age-related cognitive declines: Effects of goal specificity in maze learning. *Journal of Educational Psychology*, *93*, 181–186. doi:10.1037/0022-0663.93.1.181.

Peterson, L., & Peterson, M. J. (1959). Short-term retention of individual verbal items. *Journal of Experimental Psychology*, *58*, 193–198. doi:10.1037/h0049234.

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, *12*, 257–285.

Sweller, J. (2003). Evolution of human cognitive architecture. In B. Ross (Ed.), *The psychology of learning and motivation, vol. 43* (pp. 215–266). San Diego: Academic.

Sweller, J. (2004). Instructional design consequences of an analogy between evolution by natural selection and human cognitive architecture. *Instructional Science*, *32*, 9–31. doi:10.1023/B:TRUC.0000021808.72598.4d.

Sweller, J., & Levine, M. (1982). Effects of goal specificity on means–ends analysis and learning. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *8*, 463–474. doi:10.1037/0278-7393.8.5.463.

Sweller, J., & Sweller, S. (2006). Natural information processing systems. *Evolutionary Psychology*, *4*, 434–458.

Sweller, J., Mawer, R. F., & Ward, M. R. (1983). Development of expertise in mathematical problem solving. *Journal of Experimental Psychology. General*, *112*, 639–661. doi:10.1037/0096-3445.112.4.639.

Tarmizi, R. A., & Sweller, J. (1988). Guidance during mathematical problem solving. *Journal of Educational Psychology*, *80*, 424–436. doi:10.1037/0022-0663.80.4.424.

Taylor, D. W., Berry, P. C., & Block, C. H. (1958). Does group participating when using brainstorming facilitate or inhibit creative thinking? *Administrative Science Quarterly*, *3*, 23–47. doi:10.2307/2390603.

Torrance, E. P. (1966). *Torrance tests of creative thinking*. Princeton, NJ: Personnel.

Vollmeyer, R., Burns, B. D., & Holyoak, K. J. (1996). The impact of goal specificity on strategy use and the acquisition of problem structure. *Cognitive Science*, *20*, 75–100.