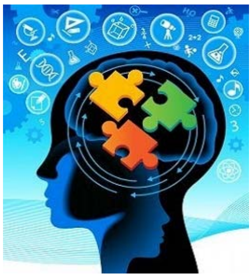
TEACHING CREATIVITY AND INVENTIVE PROBLEM SOLVING IN SCIENCE



What Is Creativity?

How to define creativity is an age-old question. Justice Potter Stewart's famous dictum regarding obscenity "*I know it when I see it*" has also long been an accepted test of creativity. But this is not an adequate criterion for developing an instructional approach. A scientist colleague of mine recently noted that "Many of us [in the scientific community] rarely give the creative process a second thought, imagining one either 'has it' or doesn't." We often think of inventiveness or creativity in scientific fields as the kind of gift associated with a Michelangelo or Einstein. This is what Kaufman and Beghetto (2008) call big-C creativity, borrowing the term that earlier workers applied to the talents of experts in various fields who were identified as particularly creative by their expert colleagues (MacKinnon, 1978). In this sense, creativity is seen as the ability of individuals to generate new ideas that contribute substantially to an intellectual domain. Howard Gardner defined such a creative person as one who "*regularly solves problems, fashions products, or defines new questions in a domain in a way that is initially considered novel but that ultimately comes to be accepted in a particular cultural setting*" (Gardner, 1993).

But there is another level of inventiveness termed by various authors as "*little-c*" (Craft, 2000) or "*mini-c*" (Kaufman and Beghetto, 2008) creativity that is widespread among all populations. This would be consistent with the workplace definition of creativity offered by Amabile and her coworkers: "*coming up with fresh ideas for changing products, services and processes so as to better achieve the organization's goals*" (Amabile *et al.*, 2005). Mini-c creativity is based on what Craft calls "*possibility thinking*" (Craft, 2000), as experienced when a worker suddenly has the insight to visualize a new, improved way to accomplish a task; it is represented by the "*aha*" moment when a student first sees two previously disparate concepts or facts in a new relationship, an example of what Arthur Koestler identified as bisociation: "*perceiving a situation or event in two habitually incompatible associative contexts*" (Koestler, 1964).

In this essay, I maintain that mini-c creativity is not a mysterious, innate endowment of rare individuals. Instead, I argue that creative thinking is a multicomponent process, mediated through social interactions, that can be explained by reference to increasingly well-understood mental abilities such as cognitive flexibility and cognitive control that are widely distributed in the population. Moreover, I explore some of the recent research evidence (though with no effort at a comprehensive literature review) showing that these mental abilities are teachable; like other higher-order cognitive skills (HOCS), they can be enhanced by explicit instruction.

Creativity Is a Multicomponent Process

Efforts to define creativity in psychological terms go back to J. P. Guilford (Guilford, 1950) and E. P. Torrance (Torrance, 1974), both of whom recognized that underlying the construct were other cognitive variables such as ideational fluency, originality of ideas, and sensitivity to missing elements. Many authors since then have extended the argument that a creative act is not a singular event but a process, an interplay among several interactive cognitive and affective elements. In this view, the creative act has two phases, a generative and an exploratory or evaluative phase (Finke et al., 1996). During the generative process, the creative mind pictures a set of novel mental models as potential solutions to a problem. In the exploratory phase, we evaluate the multiple options and select the best one. Early scholars of creativity, such as J. P. Guilford, characterized the two phases as divergent thinking and convergent thinking (Guilford, 1950). Guilford defined divergent thinking as the ability to produce a broad range of associations to a given stimulus or to arrive at many solutions to a problem (for overviews of the field from different perspectives, see Amabile, 1996; Banaji et al., 2006; Sawyer, 2006). In neurocognitive terms, divergent thinking is referred to as associative richness (Gabora, 2002; Simonton, 2004), which is often measured experimentally by comparing the number of words that an individual generates from memory in response to stimulus words on a word association test. In contrast, convergent thinking refers to the capacity to quickly focus on the one best solution to a problem.

The idea that there are two stages to the creative process is consistent with results from cognition research indicating that there are two distinct modes of thought, associative and analytical (Neisser, 1963; Sloman, 1996). In the associative mode, thinking is defocused, suggestive, and intuitive, revealing remote or subtle connections between items that may be correlated, or may not, and are usually not causally related (Burton, 2008).

In the analytical mode, thought is focused and evaluative, more conducive to analyzing relationships of cause and effect (for a review of other cognitive aspects of creativity, see Runco, 2004). Science educators associate the analytical mode with the upper levels (analysis, synthesis, and evaluation) of Bloom's taxonomy (e.g., Crowe et al., 2008), or with "*critical thinking*," the process that underlies the "*purposeful, self-regulatory judgment that drives problem-solving and decision-making*" (Quitadamo et al., 2008). These modes of thinking are under cognitive control through the executive functions of the brain. The core executive functions, which are thought to underlie all planning, problem solving, and reasoning, are defined (Blair and Razza, 2007) as working memory control (mentally holding and retrieving information), cognitive flexibility (considering multiple ideas and seeing different perspectives), and inhibitory control (resisting several thoughts or actions to focus on one). Readers wishing to delve further into the neuroscience of the creative process can refer to the cerebrocerebellar theory of creativity (Vandervert et al., 2007) in which these mental activities are described neurophysiologically as arising through interactions among different parts of the brain.

The main point from all of these works is that creativity is not some single hard-to-measure property or act. There is ample evidence that the creative process requires both divergent and convergent thinking and that it can be explained by reference to increasingly well-understood underlying mental abilities).

Creativity Is Widely Distributed and Occurs in a Social Context

Although it is understandable to speak of an aha moment as a creative act by the person who experiences it, authorities in the field have long recognized (e.g., Simonton, 1975) that creative thinking is not so much an individual trait but rather a social phenomenon involving interactions among people within their specific group or cultural settings. "*Creativity isn't just a property of individuals, it is also a property of social groups*" (Sawyer, 2006). Indeed, Osborn introduced his brainstorming method because he was convinced that group creativity is always superior to individual creativity. He drew evidence for this conclusion from activities that demand collaborative output, for example, the improvisations of a jazz ensemble. Although each musician is individually creative during a performance, the novelty and inventiveness of each performer's playing is clearly influenced, and often enhanced, by "*social and interactional processes*" among the musicians (Sawyer, 2006). Recently, Brophy (2006) offered evidence that for problem solving, the situation may be more nuanced. He confirmed that groups of interacting individuals were better at solving complex, multipart problems than single individuals. However, when dealing with certain kinds of single-issue problems, individual problem solvers produced a greater number of solutions than interacting groups, and those solutions were judged to be more original and useful.

Consistent with the findings of Brophy (2006), many scholars acknowledge that creative discoveries in the real world such as solving the problems of cutting-edge science—which are usually complex and multipart—are influenced or even stimulated by social interaction among experts. The common image of the lone scientist in the laboratory experiencing a flash of creative inspiration is probably a myth from earlier days. As a case in point, the science historian Mara Beller analyzed the social processes that underlay some of the major discoveries of early twentieth-century quantum physics. Close examination of successive drafts of publications by members of the Copenhagen group revealed a remarkable degree of influence and collaboration among 10 or more colleagues, although many of these papers were published under the name of a single author (Beller, 1999). Sociologists Bruno Latour and Steve Woolgar's study (Latour and Woolgar, 1986) of a neuroendocrinology laboratory at the Salk Institute for Biological Studies make the related point that social interactions among the participating scientists determined to a remarkable degree what discoveries were made and how they were interpreted.

In sum, when an individual experiences an aha moment that feels like a singular creative act, it may rather have resulted from a multicomponent process, under the influence of group interactions and social context. The process that led up to what may be sensed as a sudden insight will probably have included at least three diverse, but testable elements: 1) divergent thinking, including ideational fluency or cognitive flexibility, which is the cognitive executive function that underlies the ability to visualize and accept many ideas related to a problem; 2) convergent thinking or the application of inhibitory control to focus and mentally evaluate ideas; and 3) analogical thinking, the ability to understand a novel idea in terms of one that is already familiar.

What Do We Know about How to Teach Creativity?

The possibility of teaching for creative problem solving gained credence in the 1960s with the studies of Jerome Bruner, who argued that children should be encouraged to “treat a task as a problem for which one invents an answer, rather than finding one out there in a book or on the blackboard” (Bruner, 1965). Since that time, educators and psychologists have devised programs of instruction designed to promote creativity and inventiveness in virtually every student population: pre–K, elementary, high school, and college, as well as in disadvantaged students, athletes, and students in a variety of specific disciplines (for review, see Scott et al., 2004). Smith (1998) identified 172 instructional approaches that have been applied at one time or another to develop divergent thinking skills.

Some of the most convincing evidence that elements of creativity can be enhanced by instruction comes from work with young children. Bodrova and Leong (2001) developed the Tools of the Mind (Tools) curriculum to improve all of the three core mental executive functions involved in creative problem solving: cognitive flexibility, working memory, and inhibitory control. In a year-long randomized study of 5-yr-olds from low-income families in 21 preschool classrooms, half of the teachers applied the districts' balanced literacy curriculum (literacy), whereas the experimenters trained the other half to teach the same academic content by using the Tools curriculum (Diamond et al., 2007). At the end of the year, when the children were tested with a battery of neurocognitive tests including a test for cognitive flexibility (Durston et al., 2003; Davidson et al., 2006), those exposed to the Tools curriculum outperformed the literacy children by as much as 25% (Diamond et al., 2007). Although the Tools curriculum and literacy program were similar in academic content and in many other ways, they differed primarily in that Tools teachers spent 80% of their time explicitly reminding the children to think of alternative ways to solve a problem and building their executive function skills.

Teaching older students to be innovative also demands instruction that explicitly promotes creativity but is rigorously content-rich as well. A large body of research on the differences between novice and expert cognition indicates that creative thinking requires at least a minimal level of expertise and fluency within a knowledge domain (Bransford et al., 2000; Crawford and Brophy, 2006). What distinguishes experts from novices, in addition to their deeper knowledge of the subject, is their recognition of patterns in information, their ability to see relationships among disparate facts and concepts, and their capacity for organizing content into conceptual frameworks or schemata (Bransford et al., 2000; Sawyer, 2005).

Such expertise is often lacking in the traditional classroom. For students attempting to grapple with new subject matter, many kinds of problems that are presented in high school or college courses or that arise in the real world can be solved merely by applying newly learned algorithms or procedural knowledge. With practice, problem solving of this kind can become routine and is often considered to represent mastery of a subject, producing what Sternberg refers to as “*pseudoexperts*” (Sternberg, 2003).

But beyond such routine use of content knowledge the instructor's goal must be to produce students who have gained the HOCS needed to apply, analyze, synthesize, and evaluate knowledge (Crowe et al., 2008). The aim is to produce students who know enough about a field to grasp meaningful patterns of information, who can readily retrieve relevant knowledge from memory, and who can apply such knowledge effectively to novel problems. This condition is referred to as adaptive expertise (Hatano and Ouro, 2003; Schwartz et al., 2005). Instead of applying already mastered procedures, adaptive experts are able to draw on their knowledge to invent or adapt strategies for solving unique or novel problems within a knowledge domain. They are also able, ideally, to transfer conceptual frameworks and schemata from one domain to another (e.g., Schwartz et al., 2005). Such flexible, innovative application of knowledge is what results in inventive or creative solutions to problems (Crawford and Brophy, 2006; Crawford, 2007).

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