FINDINGS IN CREATIVITY AND RELEVANCE IN CIVIL ENGINEERING

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ABSTRACT: National needs, world power restructuring, and global problems demand creative solutions and innovative strategies. Creativity is the generation of ideas that are novel to the individual or to the group involved in the task. Creative productivity depends on the depth and breadth of information and on the individual's capacity for unrestricted thinking. Akin to the creative act, there is also a creative attitude, which can be stimulated or inhibited. The study of the personalities of creative individuals has revealed common cognitive and motivational traits. Neurological explanations for most of these phenomena are still lacking, however, findings already point to the importance of nurturing the brain at all ages. Several steps have been recognized in the creative process. The same steps are identified in the scientific method, and in a wide range of engineering methods. Inhibitors and stimulators of creativity can be readily found in the practice of civil engineering. Computer systems can be designed to stimulate engineers' creativity. Education and the proper design of the work environment can help develop and maintain creative abilities, with the right blend of critical thinking and engineering curiosity.

INTRODUCTION

The $109 billion 1989 deficit of the United States would have been 54% worse without the six high-technology industries, namely computers, aerospace, agriculture, commodities, chemicals, pharmaceuticals, and scientific equipment. The creative needs of these powerhouse industries, plus the increased deterioration of the infrastructure and consequently the need for new methods of inspection and repair; the decline in U.S. competitiveness in international job markets; the increased importation of innovative technology; and global concerns, such as food and environmental problems, yield some of the index that alarm analysts of national technology. In this context, the word "creativity" has frequently been mentioned, sometimes as an available asset and other times as a needed resource. In most cases, civil engineering is directly involved, either in service tasks or as a primary need.

Research, mostly during this century, has made creativity more perceptible. Its status has been changed from the obscure mythical quality reserved for the exceptional few, to a human property that can be stimulated in the true Pavlovian sense. These and other findings in cognitive science, neurobiology, artificial intelligence, and history/philosophy are significant to most activities from business to education and from arts to sciences, including civil engineering.

This paper centers on the essence of engineering: ingenuity. It presents a compilation of the state of the art on creativity, placing emphasis on the findings most relevant to the civil engineering profession.

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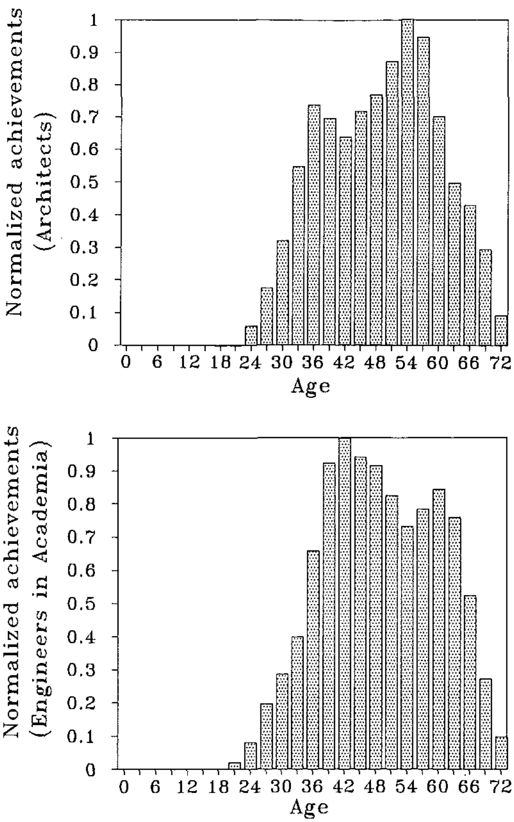

FIG. 2. Productive Creativity in Engineering (Academia) and Architecture

tivational-, and personality-related. More recently, Simonton (1988) divided the characteristics of the creative individual into two main categories: cognitive, involving: (1) Intellect; and (2) structural organization of the intellect, and motivational, comprised of: (1) Enhanced motives; and (2) suppressed motives.

Under the cognitive category, Simonton (1988) reaffirms previous findings showing that high intelligence quotient (IQ) is a necessary but not sufficient condition to guarantee creativity (Sternberg 1988; Sternberg 1986). Simonton's other features of the intellect include: (1) Originality; (2) ability to redefine problems; (3) flexibility and fluency of thought; (4) broadness; (5) elaborative and evaluative factors; (6) independence of judgment; (7) openness to the irrational; (8) dominance and self-assertion.

Simonton's motivational category places particular emphasis on the well-known fact that successful scientists are exceptionally energetic and hard working. Their individual fascination with research, partly nurtured by curiosity, and partly by the drive to excel, creates an unsuppressable intrinsic motivation. Intellectual persistence, risk-taking, tolerance of the unknown, preference for manipulative ideas, inner need for recognition, variety, autonomy, moral commitment to the world, and acceptance of criticism (McAleer 1989) are some of the other factors categorized under enhanced motives. Suppressive motives, on the other hand, include the need for extrinsic motivation and the tendency to work alone.

There have been attempts to categorize individuals by their type of personality. Most creative individuals have the type T personality (T for thrill-seeking), either T-minus (destructive thrill-seeking) or T-plus (creative and constructive thrill-seeking) (Farley 1986). These people need high arousal and stimuli that they often find intrinsically. Distinctly, the T plus individuals are more likely to have a positive impact on their surrounding society.

Is creativity a behavior, or is it deeply intertwined with one's genes? Many have believed that creativity is possessed by the privileged few. Others have postulated that creativity is a behavior; this means that it follows stimulus-response mechanisms similar to those of the appetitive behavior in Pavlov's experiments. The authors believe that there is indeed a creative attitude associated with creativity; this attitude is a behavior.

Creative Attitude

The creative attitude can be stimulated as well as inhibited. The methods used to enhance creativity either aim at increasing quantity or improving quality of the creative thoughts. Some intend to enhance permutation, others to facilitate the identification of patterns by systematically organizing information (Akhoundi and Santamarina 1990a). Bailey (1990) lists over ninety stimulators. Gordon (1961) proposed a technique known as synectics (literally meaning: joining different and apparently irrelevant elements). The system involves preparing a table (matrix) and systematically addressing the intersections of each column with each row. Derivatives of this method, sometimes known as morphological analyses or forced relationships, have also been implemented (Holt 1987; Bailey 1978).

Brainstorming is a widely known method (Feldhusen and Treffinger 1986; Osborn 1953; Hogarth 1980) consisting of two steps. First, ideas are generated without any criticism and restriction (quantity). Then the generated ideas are criticized in order to eliminate the less feasible ones (quality). Various offsprings of brainstorming have been used. The modifications to the original technique are environment- or medium-dependent. A popular method of modified environment is relaxed conditions. King (1988) applied this method in the context of a ceramics research and development (R and D) program, by moving the R and D team to a retreat. MetaPlan (MetaPlan 1989), originally developed in West Germany in 1972, uses pinboards, cards, markers, and construction paper as the mediums of communication among group members. Ideafisher (Roberts 1989; Lewis 1989), on the other hand, uses a large computer data base that helps the user brainstorm with associations. Leaving the problem aside while awaiting insight is another recommended strategy. Variations of this method include involvement in multiple projects and performing recreational activities.

There are situations that may inhibit creativity: too much involvement in a topic, willingness or necessity of remaining logical, early evaluation of ideas, habits, self-imposed constraints, unhealthy competition, and cultural conventions. A closer look at today's society reveals the existence of many of these creativity-hindering instances.

Creative Process

Creativity is not an instantaneous process, but one that consists of a sequence of mental stages. Four steps are generally accepted: preparation, incubation, illumination, and verification. Often in engineering the verification step involves elaboration of the generated ideas, their implementation, and the retrospective evaluation of performance.

Neurological Findings

The brain can be viewed at the micro and macro levels. At one end the inter- and intraparticle actions are studied (molecular range is in the scale of 1 Å); at the other end, the intercomponent operations are analyzed (central nervous system in the order of 1 m).

The brain is made of a very large number of neurons (about 100 μm in size), approximately 100 billion at birth. After a sharp loss in childhood (about 70 billion), the brain continues to lose neurons at a lower rate (50,000 per day). Neurons, whether sensory (sensors to brain) or motor (brain to muscles), consist of a cell body, a main axis (axon), and sets of branching fibers (dendrites). The nervous system is made of series of interconnected neurons. These neurons are in contact with other neurons through synapses. The functioning of the brain is based on the sequential transfer of electrochemical signals. The propagation is achieved in one direction (i.e., from the dendrites, to cell bodies, and to axons in one sensory neuron to the dendrites, to cell bodies, and to axons of the next sensory neuron). The travel of electrochemical signals along the neuron is made possible through an action potential, in a wavelike propagation of the electrochemical signal (Haskel and Sygoda 1972).

Extensive research on neurobiology in the last decades has resulted in important advances in understanding the role of brain components. However, neurology and associated fields are still far from deciphering the complexity of the brain. Much of the research has been based on laboratory animals, other animals with distinct beneficial features (i.e., squids, Aplysia), the performance of individuals with known brain damage, and the use of powerful monitoring devices [e.g., Positron-Emission Tomography (PET) scan]. The studies with animals are justified by the similarity between animal and human brains: no part or function has been found to be specific to the human brain (Changeux 1986). The species' brain differences come only in the size of various components. For instance, in man, the outer layer generally associated with higher functions, better known as cortex (gray matter), is far larger than even in the closest of species, the chimpanzee. The brain sections associated with hearing in bats, and those associated with olfaction in snakes, however, are proportionally larger than man's.

The brain and its operation are the subjects of many books. Some of the findings most relevant to this paper are: (1) The number of synapses is related to environmental characteristics, indeed, brain growth—weight, number of cells, thickness of cortex—can be affected using external stimulus; the brain can be nurtured; (2) the exposure to stimulating environment can compensate and override the effects of cell loss that accompanies aging; (3) brain cells are, in many respects, like the rest of the cells in the body—they are able to heal and reconstruct.

In one experiment, Diamond (1988) and her colleagues bypassed the effects of many generations of controlled breeding of maze-dull rats, by exposure of the comparison group to a superenriched environment. Further physical analysis of the brain tissues supported the experimental performance. This observation points to the relative importance of Darwinian selection and enriched environment, at least in short time scales. Still, the relative effects of the stimulating and hindering factors on the creative attitude and on the brain's physical capacity are difficult to assess.

These observations substantiate some of the hypothetical trends in Fig. 1 and translate to conclusions of tremendous importance; man can become fundamentally more intelligent at any stage of life, by training his brain just as he would train his muscles.

Creativity and Engineering Method

The rationalistic approach to knowledge can be traced back at least twenty-five centuries to the great Greek philosophers. Since then, it has deeply penetrated the western culture and today its presence passes unnoticed. The scientific method is the most recognized exponent of the rationalistic approach. Its underlying rationality is so well accepted that research programs that are not presented as a logically organized body of knowledge are considered nonscientific, or at best poor.

Generally, the scientific method consists of the following tasks (Winograd and Flores 1987): (1) Observation of a phenomenon that, henceforth, is taken as a problem to be explained; (2) proposition of an explanatory hypothesis in the form of a deterministic system that can generate a phenomenon, isomorphic with the one observed; (3) proposition of a computed state or process in the system specified by the hypothesis as a predicted phenomenon to be observed; and (4) observation of the predicted phenomenon. But, what is the underlying thought process? Can all alternatives be generated? Why do some individuals tend to generate more alternatives than others? Could the same individual be trained to develop more creative alternatives? Interestingly enough, the steps in the scientific method show high parallelism with the creative process (Table 1).

The scientific method has influenced all branches of knowledge. For instance, geotechnical engineering started its scientific foundation at the beginning of this century. It evolved, developing analytical procedures for in situ testing, construction methods under high uncertainty (e.g., Peck's observational method), and procedures for analysis of failures (e.g., Leonard's method). When these methods are examined, the essential similitude with the creative process becomes apparent (Table 1).

Similar analysis can be extended to engineering design processes (Akhoundi and Santamarina 1990b). Torroja (1899–1961), a famous Spanish engineer and architect, was not acclaimed for the quantity of the projects in which he participated, nor for the size of the structures he designed, but for the creative nature of his work. Torroja's account of his designs allows the reconstruction of the design process he followed (Torroja 1958a, 1958b):

1. Carefully specify a complete set of requirements for the problem (checklist), distinguishing between essential, flexible, and mere caprice.
2. Sketch the initial ideas of the envisioned structural type without restricting the imagination to widely used classical prototypes.
3. As conflicts between functional and structural requirements arise, attempt

TABLE 1. Creative Process, Scientific Method, and Engineering Decision Methods

Creativity (1)	Scientific method (2)	Torroja's design method (3)	Peck's observational method (4)	Leonard's method of analysis of failures (5)
Preparation stage	Observation	Familiarize with project	Exploration and assessment of conditions Working hypothesis Basic design	Collect information
Incubation stage	—	List requirements	Determine: conceivable deviation measureable/values	Identify special facts and features
Idea generation stage	Propose hypothesis Predict phenomenon	Sketch ideas: new adaptation combination	Propose: Alternative actions Design modifications	Postulate failure mechanisms
Elaboration stage	Elaboration	Solve conflicts Find alternatives	Calculate quantities Plan observations	Evaluate each mechanism for incompatibility with observables
Implementation and evaluation stage	Implementation Observation	Evaluation Select solution	Measurements Evaluation Design modification	Plan and conduct further investigations

to solve them, looking for alternative functional arrangements as well as overall solutions.

4. Solutions may consist of the adaptation of classical prototypes, new combinations, or an entirely new concept. Awkward steps added to adapt a classical prototype should warn of an abnormal and unsound design. Leave aside new solutions for a few days to free the imagination.

5. The selection of a solution must undergo the most stringent criticism.

Evaluation should be guided by a strong awareness of economic limitations and a strong sense of aesthetics, harmony and simplicity. The steps of Torroja's design method are also listed in Table 1.

Civil Engineering: Inhibition and Stimulation

When creativity in civil engineering is seen as a behavior, stimulating and hindering factors can be identified. For example, social needs such as the massive aging and progressive failure of the infrastructure help increase engineers' awareness, stimulating and facilitating the generation of creative solutions. On the other hand, there are personal, social and technological factors that hinder creativity. Torroja recognized that an excess of logic restricts the generation of alternatives and diminishes the beauty of the final design (Torroja, 1958b). Except for the case of unique structures that escape the realm of common practice, our legal system along with the existing standards and codes reduce today's design to cookbook solutions that greatly limit the freedom for creative design. Moreover, the organizational environment that has developed in many firms cultivates a low self-image for the engineer, taking away his creative motivation. Many of these issues have been discussed in this journal and other professional publications (e.g., Denning 1988; Terry 1989; Lurie and Weiss 1988; Meis 1989; Muspratt 1988). Computers, environment, and critical thinking are reviewed next.

Computers

Recent computer applications, including nonalgorithmic decision processes, promise an even greater involvement of computers in design and construction tasks. While the advantages computers provide cannot be disputed, it is prudent to retain a critical attitude towards the use of computers, their consequences in decision making, and their effects on users [ASCE's *Quality in the Constructed Project* (Fox and Cornell 1988) insists on the responsible use of computer methods without compromising competence or mature judgment].

Findings in cognitive psychology on the limitations in human decision making, in conjunction with the early advances in artificial intelligence (AI) led many researchers to conclude that it was possible to replace man by his strategies. Today, it is well documented that computers can surpass people in bounded tasks, such as games, but not necessarily in complex ones. Complex software and systems that are incrementally built by trial and error are bound to have errors and be brittle. In the case of expert systems, implementation must be cautious: the pretentious name, the type of application (e.g., decision-making), and the public misinformation may result in users' abandonment and blind acceptance of systems decisions. This is already a problem among users of algorithmic programs. Users' alienation to the system, their lack of skepticism, and a lessening of creativity can lead to higher costs, lower rates of safety in the built environment, and lower levels of technological innovation.

In recent years the need to adapt man to machines, has been replaced by the need to adapt machines to man. In the case of computers, this is done by means of well-designed interfaces. An adequate interface eases the user acceptability and enhances performance; an inadequate interface discourages the user from learning and creating, thereby reducing the quality of results. Indeed, the goal should not be the use of technology to dull individuals and weaken their capabilities, but to bring out the best in each individual while interacting with a computer. Researchers agree on the inadequacy of current interface designs (e.g., Bendapudi and Tepfenhard 1988). Human limitations and capabilities are of fundamental importance to the design of interfaces. Design must emphasize the complimentary nature of human computer interaction, using human capability of recognizing patterns and unusual elements, improvising inductive decisions, overriding own action, or modifying performance with experience (Wickens 1984).

Man and machine can interact at various levels depending on the amount of human involvement, and the type of creative process. These levels of interaction are shown in Fig. 3. While at one end man stands alone (human experts), unassisted by machines, at the other end the machine stands unassisted by man (the ideal Turing machine). The first level at which man and machine interact, represents the state-of-the-art algorithmic software. At this level, nonalienating interfaces and user-centered programming improve the usability of the software (Gould and Lewis 1983; Akhoundi and Santamarina 1988). The second level of interaction involves the machine used in conjunction with man, engineers in this case, in order to assist man in his creative tasks. Support Systems for Creativity (Akhoundi and Santamarina 1989), Ideafisher, and Cyberquest are examples of this category [other examples can be found in Mindware (1990)]. The next level of interaction, not depicted in Fig. 3, includes large software systems that perform tasks

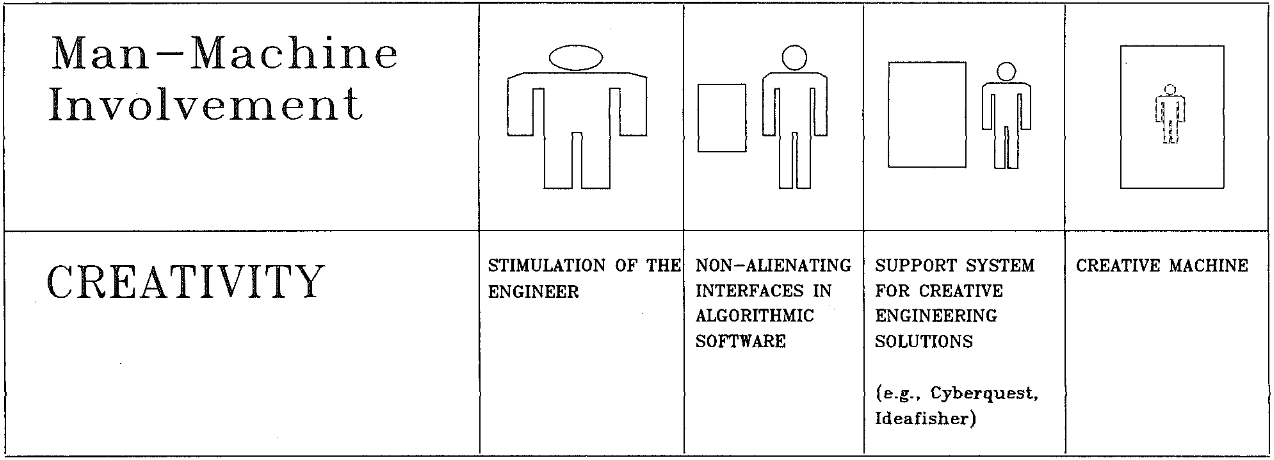

FIG. 3. Creativity and Man-Machine Interaction

with little or no human supervision. These systems tend to be brittle and lead to potentially dangerous situations, such as Three Mile Island, mismanagement of accounts in a major bank, and freezing of a national phone system. In this case, the potential role of creativity may be at the design level. The creative machine is the extreme case and represents in part the AI goal. While the possibility of its existence is arguable, its development has stimulated a large body of research.

Environment, Task, and Alienation

It has been indicated that human behavior can only be defined by virtue of the context in which it occurs. Work on alienation has centered around the study of office and factory workers. Shepard (1971) discusses several manifestations of alienation in factory workers: (1) The feeling of being controlled by the equipment/system without being able to modify this condition; (2) the inability to understand the ongoing processes and their relevance to the overall solution; (3) the attitude to value work as a means to nonwork ends rather than for its intrinsic rewards; and (4) low involvement in his work, which is considered an insignificant part of his life. It was also observed that levels of alienation in factories were lowest in manual and fully automated tasks, while they were highest in the intermediate condition of mechanized tasks. Similar perception is not uncommon among young engineers working in either public or private organizations. In such an environment, the critical thinking ability is diminished.

Critical Thinking, Skepticism, and Curiosity

Critical thinking complements creativity. A major social problem that has emerged in recent years is the lack of critical thinking skills in the classrooms. This deficiency has been blamed on the preventive and authoritative teaching methods. Current efforts aim at rebuilding the critical thinking abilities in the course of educational training. Wasserman (1987) recommends thinking operations that help improve critical thinking in a classroom. They include: comparing, interpreting, observing, summarizing, classifying, making decisions, suggesting hypotheses, imagining and creating, criticizing and evaluating, designing projects and investigations, identifying assumptions, applying principles in new situations, coding for certain patterns of thinking, gathering and organizing data. In addition, stimulating critical thinking requires the right combination of authority and encouragement that pushes the individual to respond to the challenge of the problem, without downgrading creativity.

Often along with critical thinking, another attitude manifests itself: skepticism. Skepticism is the attitude of doubting. Some skepticism is needed to optimize creative decision making. Its absence can result in incorrect or poor conclusions; however, too much skepticism can halt creativity. The authors have noted that certain circumstances trigger the skeptical perception of interacting parties. These include: (1) Disregard for human capabilities on the bases of one's prejudices or as a result of the other party's poor prior performance; (2) lack of logical sequencing in the presentation of data; (3) irrelevant, inappropriate or uncertain feedback; and (4) unconventional physical appearance and insecurity. On the other hand, lack of personal interest, a preset receptive and conformist attitude as well as highly competitive or aggressive environments reduce one's skeptical attitude.

Scientists are driven by curiosity. But engineers are often encouraged to conform rather than let the curiosity serve as a drive for further inquiry. Curiosity is the urge to investigate the environment, particularly when it is novel or unusual, and acts as a motivational drive for creativity. Stimuli for curiosity include the excitement of discovery, the challenge of unknown, intrinsic motivation, and sometimes fear (Thomas and Schneider 1984). Environments that do not call upon the novel and the surprising may inhibit curiosity. In addition, boredom may develop after lengthy exposures to situations that would otherwise be considered stimulating.

Conclusions

Creativity depends on the information base and the capacity for unrestricted thinking. There is an associated creative attitude that can be stimulated as well as inhibited.

Motivated engineers reach a peak of creative productivity in their mid 40s and a second peak about 15 years later. Today, there is sufficient evidence to conclude that every individual can become more creative at any stage in life, if he is willing to invest the effort or if environmental conditions stimulate him to do so. Proper stimulation produces changes not only at the psychological level, but also within the inner neurological structure.

Beyond the apparent logical completeness and integrity of the rationalistic approach, creativity plays a fundamental role in the scientific method, as well as in engineering decision processes. Indeed, it seems that these methods are guided towards the stimulation of creative problem solving.

Several stimulating and inhibiting factors can be identified in the profession. Computers can play either role. In many cases, they have led to users' alienation, manifested in the lack of skepticism towards the system and its output and in the diminished curiosity and creativity in computer-based problem solving. However, computer systems can be developed to stimulate the user and to help the generation of creative engineering solutions. Education and the proper design of the work environment can help develop and maintain creative abilities, with the right blend of critical thinking and engineering curiosity.

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