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Creativity, problem solving and innovative science: Insights from history, cognitive psychology and neuroscience

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This paper examines the intersection between creativity, problem solving, cognitive psychology and neuroscience in a discussion surrounding the genesis of new ideas and innovative science. Three creative activities are considered. These are (a) the interaction between visual-spatial and analytical or verbal reasoning, (b) attending to feeling in listening to the 'self', and (c) the interaction between conscious and non-conscious reasoning. Evidence for the importance of each of these activities to the creative process is drawn from (a) historical and introspective accounts of novel problem solving by noted scientists and mathematicians; (b) cognitive psychology and neuroscience; and (c) a recent empirical study of novel mathematics problem solving. An explanation of these activities is given in terms of cognitive neuroscience. A conceptual framework connecting each of these activities is presented and the implications for learning and teaching considered.

Creativity, problem solving, cognitive psychology, neuroscience

INTRODUCTION

The questions 'From where do new ideas come?, How do they arise?, and Do feeling and intuition play a role?' continue to fascinate scholars and lay people alike. Over the centuries, answers to such questions have varied. Five hundred years ago, in English and European culture, the answer quite simply, was that new ideas come from God (Pawson, 2003). In the period of rationalism that followed, the prevailing answer was that new ideas arose through reason alone (Lacey, 1996). In the reactionary romantic period that ensued, the answer was to be found in 'a way of feeling', 'an intuition' or 'an imagination' (Horowitz, 2004). In the present day climate of relativism the answer supposedly is to be found in the relative nature of experience and culture (Swoyer, 2003).

While none of these perspectives on its own offers complete and efficacious answers to our questions it seems likely that all have some merit and that the way forward must involve a synthesis of elements from the past and ideas from the present. Identifying some of these elements as well as describing the way in which these elements may interact in a cognitive explanation of the origin of new ideas, underlies the purpose of the research documented in this paper.

In particular, elements relating to different kinds of reasoning (indicative of the rationalist period) together with those of feeling and intuition (indicative of the romantic period) are discussed. Further it is argued that creativity may arise from the interactions occurring between each of these elements both cognitive (thinking and reasoning) and non-cognitive (feeling and intuition). This is done within the context of novel problem solving as it relates to scientific and mathematical experience.

BACKGROUND

On Defining Creativity in the Education Context

The literature is replete with many definitions of creativity. Some definitions focus on the product of creativity, some on the person who is creative and some on the process of creativity. Still other definitions focus on the environment where creativity occurs. The meaning of the term 'creativity' as used in this article is one adopted by the majority of investigators in the field. Put simply it means 'the production of effective novelty' (Cropley, 1999; Lubart, 2001; Mumford, 2003; Sternberg and O'Hara, 1999). Thus for creativity to be manifest, the qualities of both novelty and usefulness must be expressed. Speaking gibberish, for example, may be novel but since it is not meaningful, it is not, by such a definition, an example of creativity because it is not useful. Further, while creativity may be expressed in many different forms such as a theory, a poem, a dance, a chemical, a process, or a symphony to mention but a few, the form of effective novelty under consideration in this study, is that of successful creative problem solving carried out within the fields of science and mathematics.

It must be pointed out that the production of effective novelty is relative to the originator. Consequently, if an individual creates an effective solution to a novel problem that others have solved previously, so long as the problem solved is novel and new to the individual concerned, then creativity is considered to have been expressed. Therefore the definition of creativity applied in an educational context is not restricted to the eminent variety but is inclusive of more modest achievements of the everyday kind.

The Classical Model of Creative Problem Solving

In defining the relationship between creativity and problem solving it is necessary to examine what makes creative problem solving creative. Such an examination necessitates an investigation into the creative process.

One of the earliest models of the creative process was that espoused by Wallas (1926) and Hadamard (1945) early last century. Many current day models of the creative process can be mapped to an adaptation of this early model (Aldous, 2005). Therefore the classical model is worthy of some elaboration here and is referred to in later discussion.

Four distinct phases, mark the classical model. These are **preparation**, **incubation**, **illumination** and **verification**. During the preparation phase, the problem is identified, information is gathered and conscious thoughts stirred. Although a solution may be found during this phase, for more complex and novel problems, the individual may well give up for a time. It is this temporary abandonment that leads to the incubation phase. During incubation ideas are free to associate and restructure without the individual directly working on them. It may last for a few seconds, hours or years depending on the situation. Eventually when a solution manifests itself the illumination phase has arrived often recognized as the so called 'aha' experience. Hadamard (1945) explained illumination as the unconscious mind dropping the solution into the fringe of consciousness whereupon the conscious mind seized the new idea as a moment of insight. Ultimately the identified solution needs to be checked, developed and refined in the verification phase and elaborated on to ensure its capability of being understood. Should the verification phase show a solution to be unworkable then there may be a return to an earlier stage of the creative process. Although the phases of preparation and verification are marked by conscious activity, the phases of incubation and illumination may include non-conscious activity.

Cycles of Feedback and Non-Cognitive Activity

Building on the work of Hadamard(1945) and others, Shaw (1989) undertook a study of creativity in the scientific domain. In particular, he invited a number of scientists and engineers to reflect on their creative activity. Of note was the discovery of a series of emotional poles (both positive and negative) that mapped to different stages of the creative process. This finding, along with the work of others in the field (see for example Cropley 2001, and Russ 1999)has indicated a role for non-cognitive activity in the creative process.

Overlayed on these poles of emotion Shaw (1989) theorised the presence of a series of five feedback loops. The first feedback loop known as the 'Arieti loop' predicts cycling between conscious and unconscious thinking that occurs between the phases of preparation and incubation. The second loop, termed the 'Vinacke loop' predicts non-conscious and conscious cycling between the phases of incubation and illumination. The third cycle termed the 'Lalas loop' predicts cycling between the stages of illumination and verification or explication, with the idea that further verification leads to further illumination. The fourth cycle, known as the 'Communication loop', anticipates feedback arising between the stages of verification and ongoing validation of the creative product or outcome. Finally multiple feedback loops, involving both conscious and non-conscious mental activity are theorized to exist from the verification and validation stages of creativity to all previous stages in the creative process. These multiple feedback loops are collectively referred to as the 'Rossman loop'.

A diagram summarizing the four stages of the classical model of creative problem solving (Hadamard, 1945; Wallas, 1926) together with the theorized cycles of feedback (Shaw, 1989) is given in Figure 1.

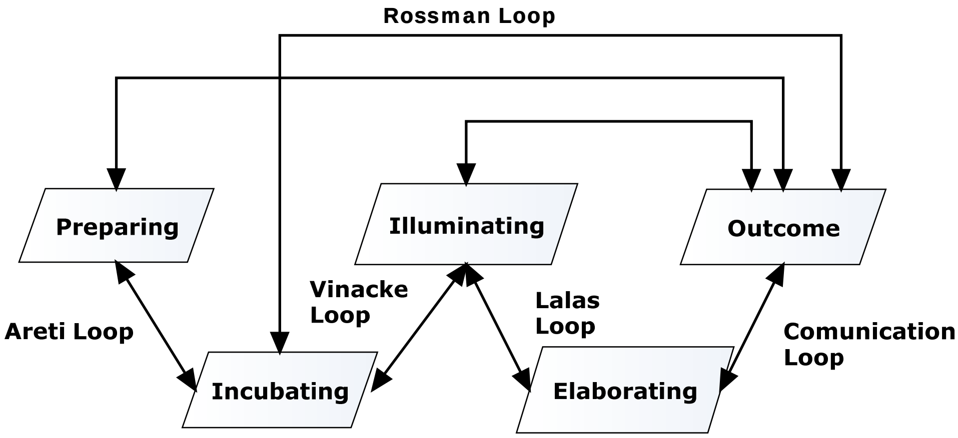

Figure 1: Diagram of the classical model of creative problem solving superimposed with Shaw's feedback loops

One process definition of creativity which takes account of such oscillatory behaviour and the affective dimension described above is that by Koberg and Bagnall (1976). This definition of creativity is described as:

> … both the art and the science of thinking and behaving with both subjectivity and objectivity. It is a combination of feeling and knowing: of alternating back and forth between what we sense and what we already know. (Koberg & Bagnall, 1976, p.8)

Therefore a critical question becomes 'What cognitive and non-cognitive activities can be found that may be used to construct a framework of creative problem solving useful to a cognitive explanation on the origin of new ideas?' A discussion of three critical activities important to both mathematics and science learning and teaching follows.

PURPOSE OF THE STUDY

A recent study on creativity and problem solving, involving the protocol analysis of five expert problem solvers, followed by a large scale quantitative analysis of 405 individuals, posited that creativity involved the interplay of three activities(Aldous, 2005, 2006). These activities were:-

- the interaction between visual-spatial and analytical/verbal reasoning,

- attending to feeling in listening to the 'self', and
- the interaction between conscious and non-conscious reasoning.

This article further examines the validity of these activities drawing evidence from (a) historical and introspective accounts of novel problem solving by noted scientists and mathematicians; (b) cognitive psychology and neuroscience; relating this evidence to (c) the findings of the recent empirical study(Aldous, 2005, 2006) The implications for learning and teaching, are then considered.

THREE CRITICAL ACTIVITIES

The Interaction between Visual-Spatial and Analytical or Verbal Reasoning

A historical introspective account

It has been asserted that introspection supported by historical data is invaluable for exploring scientific creativity (Miller, 1992) and moreover that some generality across case studies can be made(Gruber and Wallace, 1999).

One in-depth study(Miller, 1989, 1992) that utilized historical data from both primary and secondary sources including autobiographical notes and reports of introspection pertain to Albert Einstein's invention of the special theory of relativity. Of relevance to the argument presented here is Einstein's well developed use of visual-spatial thinking and analytical "wondering" (Miller, 1992, p.409). "Wondering" according to Einstein:

> seems to occur when an experience comes into conflict with a world of concepts which is already sufficiently fixed within us. (Einstein 1949 p.9 Autobiographical notes, cited in Miller, 1992, p.409)

This "wondering", although often spontaneous, usually depended for its success on "a feeling for what is a fundamental problem"(Miller 1992, p.409). One wondering and thought experiment persisted for 10 years. In this thought experiment:

> Einstein imagined what the consequences would be of running alongside of and then catching up with a point on a light wave. (Miller, 1992, p.406)

The wondering around this visual thought experiment eventually gave rise to the "germ of the special theory of relativity" (Einstein1949 p.53 Autobiographical notes, cited in Miller, 1992, p.406). Later Einstein commented:

> During all those years there was a feeling of direction, of going straight toward something concrete. It is, of course very hard to express that feeling in words… But I have it in a kind of survey, in a way visually. (Einstein, 1949, p.53 Autobiographical notes, cited in Keller, 1983, p.150)

In a letter to Hadamard, Einstein (1949, Autobiographical notes, cited in Miller 1992 p.409) further stated that creative thinking occurred in visual thinking and that words followed. The visual images were abstracted from phenomena observed in the world of sense perception and used to intuit solutions to problems concerning theoretical asymmetry not observed in nature. For example, Einstein's purpose in inventing light quanta was to overcome the anomaly concerning the discontinuous particulate source of continuous wave radiation. In Einstein's creation, light quanta represented both particulate sources and particulate radiation(Miller, 1992).

Miller (1992) concluded that Einstein's analytical "wondering" and use of visual thought experiments were critical to the development of new ideas in physics.

Given Einstein's apparent interaction between visual-spatial and analytical reasoning it is perhaps not surprising to find in a more recent study of creative problem solving, expert problem solvers oscillating between visual-spatial and analytical reasoning when successfully solving a novel problem in mathematics (Aldous, 2005, 2006) Like Einstein the visual-spatial "wondering" was associated with a feeling for the nature of the underlying problem and its solution. Some verbal protocols from the reported study evidencing visual-spatial and analytical activity are recorded below.

> I'm just trying to visualize patterns in my head … I definitely feel that the shapes are going to be geometric. (Anne)
>
> So I'm putting markers on the shape just so I can get a visual feel for the shape. (Barbara)

Cognitive psychology and neuroscience

In neurobiology and cognitive psychology, brain-imaging and behavioural data have been used to locate two brain circuits involved in scientific and mathematical thinking (Dehaene, Spelke, Pinel, Stanescu, and Tsivkin, 1999). One circuit has been found to be used for approximate arithmetic (e.g. sense of numerical magnitude) and recruits the bi-lateral areas of the parietal lobes within the brain. It is a region strong in visual-spatial processing. The other circuit has been found to be used for exact arithmetic and recruits the left inferior prefrontal cortex. This region is strong in linguistic processing. The location of these regions is shown diagrammatically in Figure 2.

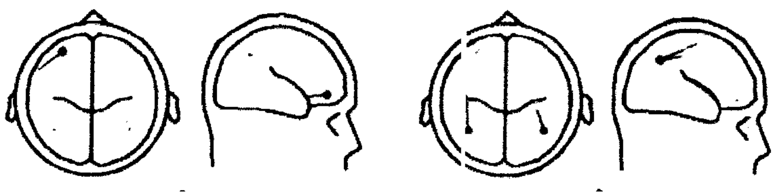

Figure 2: The first two diagrams show the location of the left inferior frontal cortex in both planar and lateral views. The second two diagrams show the location of the bilateral parietal lobes in both planar and lateral views. (Diagram adapted from Dehaene et al 1999, p.973)

The circuit involved in approximate arithmetic is language independent (ie non-verbal) and is involved in analogical mental transformations as well as visual-spatial processing. Non-verbal representations of number magnitude, "akin to a mental 'number line'" are thought to manipulate quantities in an approximation process (Dehaene et al. 1999, p.971). By contrast the circuit involved in exact arithmetic is language dependent and employs networks involved in word association processes. Exact arithmetic has been found to transfer poorly to a different language. Finally, a more recent study proposes that numerical-spatial interactions arise from common parietal circuits within the brain(Hubbard, Piazza, Pinel and Dehaene, 2005).

Interestingly, discussion in the literature over the nature of intuition, and in particular of mathematical intuition, has debated the relative merits of linguistic competence and visual spatial representation (Das, 2003; Hadamard, 1945; Krutetskii, 1976/1980). Of interest to the argument documented in this paper therefore, is the suggestion by Deheane et al (1999) that mathematical intuition arises from the interaction between these visual spatial and linguistic brain circuits.

Implication for learning and teaching

Thus, from a neurobiological perspective, encouraging students in science or mathematics classrooms to use their visual spatial and imaginative capabilities, followed by analytical and verbal documentation is likely to be helpful in assisting them to be successful in finding creative solutions in a novel problem-solving event.

Attending to Feeling in Listening to the Self

A historical introspective account

It should be noted in the introspective accounts given above, that a feeling of knowing, a feeling of cognition, a feeling of connection or a feeling of direction was being used to guide the reasoning process. Moreover this feeling was frequently associated with visual spatial activity and imagery.

Nobel prize winner and cytogeneticist Barbara McClintock, is credited with using an unusual feeling approach when deriving her theory of jumping genes. This feeling was used to guide thinking, giving greater insight into the nature of things. Indeed the corn kernels with which she worked were the subject not the object of her research (Keller, 1985). Looking for patterns of individual difference on successive generations of corn kernels, McClintock knew the biography of every cob.

> The important thing is to develop the capacity to see one kernel that is different, and make that understandable… if (something) doesn't fit, there's a reason, and you find out what it is. (McClintock cited in Keller, 1983, p.xiii)

By her own account, such careful attention gave rise to a feeling of affinity with the corn plants with which she worked that even extended to their chromosomes.

> I found that the more I worked with them, the bigger and bigger (the chromosomes) got, and when I was really working with them I wasn't outside, I was down there. I was part of the system. I was right down there with them, and everything got big. I even was able to see the internal parts of the chromosomes … It surprised me because I actually felt that these were my friends… . (McClintock cited in Matthews 1993 p .)

Of relevance to the argument presented in this paper is the fact that McClintock's "feeling for the organism" (Keller,1983, p. 101) enabled her to observe phenomena about corn genetics that others had missed. Indeed, according to McClintock "Right and left … they miss what is going on" because of the tendency to call a single difference "… an exception, an aberration, a contaminant" (Keller, 1983, p. xiii.). Thus observation of detail and attention to feeling, is important to the creative process and the development of new ideas in the production of innovative science.

One celebrated mathematician, who by his own introspective report, also used feeling to arrive at a new intellectual order was Henri Poincaré (Miller, 1992).

> If I have the feeling, the intuition so to speak of this order, so as to perceive at a glance the reasoning as a whole, I need no longer fear lest I forget one of the elements, for each of them will take its allotted place in the array, and that without any effort of memory on my part. (Poincare, 1924,p. 385, original 1908)

In placing high value on this aesthetic feeling, Poincaré wrote in an essay entitled "Mathematical Definitions and Education", that "it is by logic we prove, it is by intuition we invent" and that "Logic, therefore remains barren unless fertilized by intuition"(cited in Miller, 1992, p.394) .

It is therefore interesting to note Einstein's definition of intuition as one also relying on a feeling for or connection with the phenomena under study

> There is no logical path leading to these laws (of nature) but only intuition, supported by sympathetic understanding of experience. (cited in Miller, 1992 p. 408)

and furthermore that "the really valuable factor is intuition"(Beveridge, 1950, p.68).

These historical accounts are not inconsistent with the finding of the recent study of creative problem solving (Aldous, 2005; 2006) that attending to feeling in listening to the self is important for the creative process. Some verbal protocols from this study, indicating an important role for feeling and intuition, are recorded below.

> Some numbers **feel** prime to me. Some answers I get don't **feel** good and those ones usually aren't. (David)
>
> It was a case in part of trying to determine why my intuitive **feeling** was my intuitive **feeling**. (Eddie)
>
> I could **feel** it. I could actually **feel** it in my brain. The analysis would take over, and then that would reach a dead end and then I would look for some intuition of where to go. I could **feel** it happening in my head. (Barbara)
>
> I'm thinking the images but **feeling** their correctness. (Anne)

Cognitive psychology and neuroscience

Neuro-scientific evidence indicates that certain processes related to emotion and feeling are indispensable to rational thinking(Damasio, 1994). In his book, *Descartes's error: Emotion reason, and the human brain,* Damasio (1994) describes cases in which lesions in a small frontal area of the brain impaired the connection between reasoning and feeling. The patient was perfectly rational on all psychological tests and yet was unable to bring reasoning to any practical conclusion. Without feeling, the patient was unable to decide which of two rational alternatives was better.

While the common view holds that under certain circumstances emotion and feelings may be detrimental to reasoning, it is more surprising to read the finding that:

> the *absence* of emotion and feeling is no less damaging, no less capable of compromising the rationality that makes us distinctly human and allows us to decide in consonance with a sense of personal future, social convention and moral principle. (Damasio, 1994, p. xii, italics in original)

and that :

> feelings point us in the proper direction, take us to the appropriate place in a decision-making space, where we can put the instruments of logic to good use … Emotion and feeling , along with the covert physiological machinery underlying them, assist us with the daunting task of predicting an uncertain future and planning our actions accordingly. (Damasio, 1994 p. xiii)

In highlighting the role of feelings in the making of rationality Damasio(1994) points out that, in order to strengthen rationality, greater consideration needs to be given to the world within, particularly to the elements of feeling and intuition. Indeed, according to Damasio (1994, p.xv) "feelings are just as cognitive, as other percepts" and that "educational systems might benefit from emphasizing unequivocal connections between current feelings and predicted future outcomes" (Damasio, 1994, p.247).

Hence, according to the weight of evidence presented thus far, it appears that listening to the self through attending to feeling is important in successfully solving a novel problem. Further, in a large scale study of 405 novel problem solvers, no successful solution was reached from a state independent of a feeling approach to reasoning (Aldous 2005).

Implication for learning and teaching

Thus, from a cognitive neuroscience perspective, encouraging students to attend to intuitive feeling is likely to increase their chances of reaching a successful solution in any novel mathematical or science problem-solving event. This has implications for mathematics and science learning and teaching and highlights the importance of the affective domain in developing new ideas and deriving innovative science.

The Interaction between Conscious and Non-Conscious Reasoning

A historical introspective account

Noted chemist Friedrick August von Kekulé is credited with deriving the structure of the benzene carbon ring. However the striking feature about this discovery, is that after having worked on the problem for a long time, he is reported to have done so from a non-conscious dream-like state. In his dream-like state, atoms writhing in snake-like motion folded back on each other to from a ring(Weisberg, 1993). Kekulé reported the dream, in the following words, in a speech at a dinner commemorating the discovery.

> I turned my chair to the fire and dozed. Again the atoms were gamboling before my eyes. This time the smaller groups kept modestly to the background. My mental eye rendered more acute by repeated vision of this kind, could now distinguish larger structures, of manifold conformation; long rows, sometimes more closely fitted together; all twining and twisting in snakelike motion. But look! What was that? One of the snakes had seized hold of its own tail, and the form whirled mockingly before my eyes. As if by a flash of lightening I awoke … Let us learn to dream, gentlemen. (Weisberg, 1993, p. 149-150)

Cognitive psychology and neuroscience

Interestingly, cognitive psychology has identified two systems of reasoning (Epstein, 1994; Sloman, 1996). One of these, the rule based or rational system, is characterized by conscious activity. The other, an associative or experiential system, is characterized by non-conscious activity. Indeed Epstein (1994) proposes that creativity, among other higher order functions, involves the complex processing of both the experiential and rational systems.

The recent study of novel problem solving documented herein, found expert problem solvers drawing on non-conscious reasoning to solve novel problems. In particular, such experts derived a valid solution to a novel problem using associative patterns of reasoning yet could give no logical explanation as to why this should be the case. Only with further questioning was a conscious explanation derived through the process of conscious rule based reasoning (Aldous 2005). Some examples of protocols evidencing non-conscious activity are given below.

> I must admit, when I was drawing it … I didn't know the solution until I'd finished drawing it. You know what I mean? I must have had a glimmer of it in my head. It was almost like my head wasn't controlling my hand … my subconscious just fully took over. (Anne)

> It's something I've always known about myself mathematically that if I can't see the answer straight away if I just sort of let my head go fuzzy and stare at it (i.e. the problem), it comes. The answer just comes. (Barbara)

> I've got to say, it used to worry me … that I didn't appear to be thinking, like other people think, or … how I thought other people thought … For me to actually think about it … was actually more the emptying of the mind than the filling of it. But I pretty well always got the right answer. (Barbara)

> … it was a case of the method that I suggested occurred almost sort of naturally as being the way one would go about the problem in an optimal fashion, and so when I got my initial '8' I was reasonably confident about it on an almost intuitive basis, because it just seemed to me the obvious way to do it … . (Eddie)

Interestingly, an important role for the psychological states of defocused attention and pre-conscious activity, have been identified in studies involving the biological basis of creativity(Martindale, 1999). According to Martindale (1999, p.149) such states could arise in three ways: “low levels of cortical activation, comparatively more right than left hemisphere activation, and low levels of frontal-lobe activation”. Further an important role for non-conscious activity was evidenced in recent experimental research seeking to enhance creativity by switching off the left fronto-temporal lobe using transcranial magnetic stimulation (TMS) (Snyder, Bossomaier and Mitchell, 2004; Snyder, Mulchany, Taylor, Mitchell, Sachdev, Gandevia, 2003; Young, Ridding and Morrell 2004) . Higher order functioning involving mind-sets, it was thought got in the way of seeing information in different ways (Phillips, 2004). By switching off higher order mind sets for short periods of time, it was theorized that, creativity would be enhanced. Although Snyder and Mitchell (1999) advocated that extraordinary skills (including mathematics and drawing) were within us all, Young and co-workers (Young et al, 2004) argued that such skills were likely to be possible for some but not all.

However, the evidence generated from this experimental research, while promising is not yet conclusive (Phillips, 2004). Nevertheless, when taken in concert with data reported in the recent study of creative problem solving(Aldous, 2005, 2006) together with historical accounts of introspection, such neurological research provides food for thought regarding the significance of the defocused state in realizing a creative idea. It also points to the important role of incubation, carried out at a range of levels of awareness to the creative process.

Implication for learning and teaching

Therefore according to the evidence presented herein, it appears that there is merit in allowing students time to incubate on a novel problem and in encouraging them not to give up because a solution is not immediately apparent. Setting a task aside for a period of time may well permit some non-conscious activity to manifest itself. Having said this however, it is likely to be necessary to apply conscious mental activity in explaining the outcome.

BRINGING IT ALL TOGETHER: CONSTRUCTING A FRAMEWORK

Summarizing the findings to date, evidence has been presented to indicate that creativity: (a) relies on preverbal and non-verbal processes including visual spatial thinking (b) involves pre-conscious activity; and (c) may give rise to a feeling or intuition. Further it appears likely that creativity involves oscillating between thinking and feeling and moving between focused and defocused states of attention. In synthesizing evidence derived from historical introspective accounts of the past, with the cognitive neuroscience and empirical studies of the present, a number of elements emerge:

- visuo-spatial and linguistic circuits of the brain;
- conscious and non-conscious mental activity; and the
- generation of feeling in listening to the ‘self’ including that of intuition.

If these elements are superimposed onto the classical model of creative problem solving, together with the cycles of feedback identified by Shaw (1989) a clear framework emerges. This framework is presented in Figure 3.

In Figure 3, Self State One is aligned with non-conscious processing and Self State Two with conscious processing. The element connecting these two states of self is the Intuitive function. It is proposed that the Intuitive function acts as an evaluative filter involved in the generation and interpretation of feeling. Further, the Intuitive function mediates the interactions of the visuo-spatial and linguistic circuits.

The Areti loop, aligned with cycles of feedback between the phases of preparation and incubation in the classic model of creative problem solving is associated with cycling between Self State One and Self State Two. This cycling may occur through the visuo-spatial and linguistic circuits. It may also occur through the Intuitive function. The Vinacke loop, aligned with cycles of feedback between the phases of incubation and illumination, is associated with cycling between Self State One and the Intuitive function. The Lalas loop, aligned with cycles of feedback between the phases of illumination and elaboration is associated with cycling between the Intuitive function and Self State Two. The Communication and Rossman loops are associated with cycling between Self State Two, the problem-solving outcome and every other phase of the creative problem solving process. The extent of recycling depends on the validation of the problem-solving outcome. Finally, a complete validation of the outcome may result in the individual exiting the creative problem solving process entirely, while a partial validation may result in the individual revisiting any stage or stages in the creative process, namely preparation, incubation, illumination or elaboration.

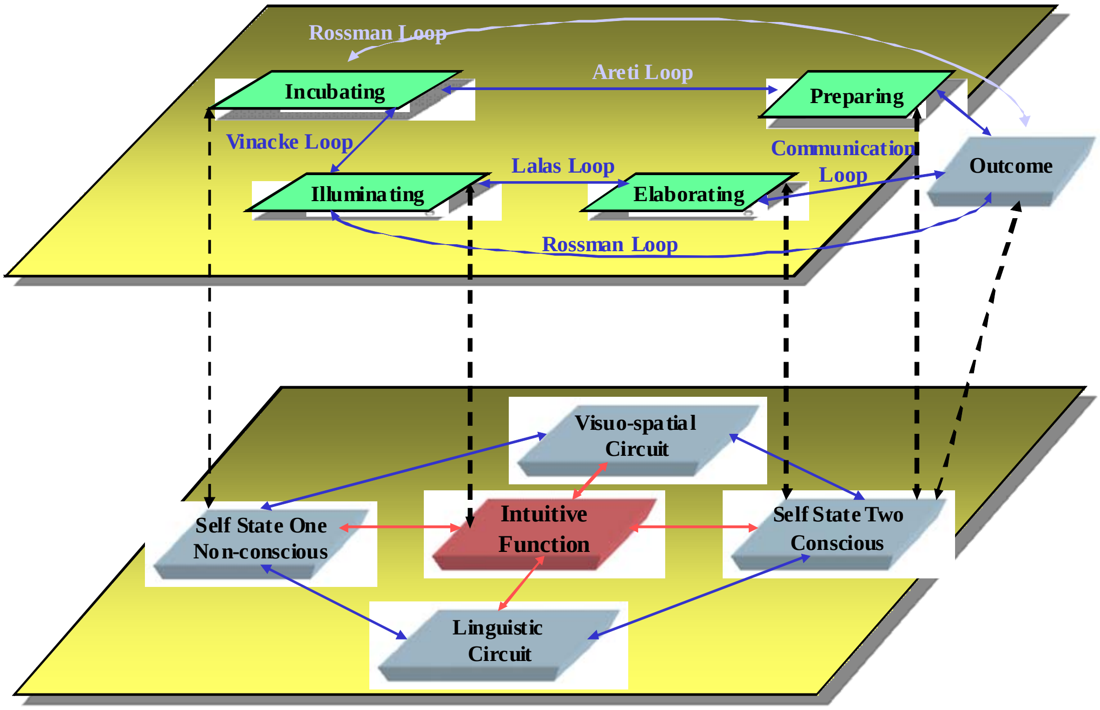

Figure 3: The conceptual framework of creative problem solving and cycles of feedback

CONCLUDING COMMENTS

Based on evidence presented in this paper, the representation of creativity posited in this framework suggests that unless cycling between Self State One and Self State Two gives rise to a feeling, such as that interpreted by the Intuitive function, then a successful solution to a novel problem solving event or the generation of a new ideas is unlikely. Similarly unless cycling between the visuo-spatial and linguistic circuits gives rise to a feeling then the likelihood of finding a successful solution will also be low. Just as Einstein, Poincare and McClintock arrived at new intellectual orders by following a feeling, so too does this framework place high value on attending to feeling in the recognition and evaluation of new ideas. This high value is predicated on the central placement of the Intuitive function within the framework.

Consequently, in characterizing the successful novel problem solver, this framework predicts that such individuals attend to feeling in listening to the self. As such they are likely to take the paths that operate through the Intuitive function. By contrast unsuccessful individuals in a novel problem solving event, this framework predicts, are those that operate through paths external to the Intuitive function. Such individuals are likely to fail to attend to feeling in listening to the self.

Given the evidence presented from historical introspective accounts, from cognitive psychology and neuroscience and from a recent study of creative problem solving educators would do well to attend to the non-cognitive as well as the cognitive elements in science and mathematics learning and teaching. While the gap between what is known about the non-cognitive elements of feeling and intuition and its role in learning and teaching is large

> the role of emotion in cognition holds the potential for important innovations in the science of learning and the practice of teaching. (Immordino-Yang and Damasio, 2007, p.10)

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