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CREATIVITY AND LONG-TERM POTENTIATION: IMPLICATIONS FOR DESIGN

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ABSTRACT

An emerging research trend has seen concepts from cognitive psychology applied to enhance the creative design process through a more detailed understanding of the underlying cognitive mechanisms. However, the physiological processes by which the human element achieves creative solutions have only recently received significant attention. Understanding the mechanisms that allow the brain to change in response to experience may have implications for creative thought processes. Long-term potentiation (LTP) is one such mechanism, and has already been implicated in learning and memory development. This paper presents a theoretical-physiological explanation of creativity, implicating LTP as a modulator of neural networks. The proposed model is applied to explain existing creativity phenomena, including fixation, incubation, and obstacles in design-by-analogy. The model is then used to describe existing, and propose new methods for overcoming obstacles to creativity in design. The results of a study, which tested one application of the theory – the effect of physical activity on fixation, are also discussed.

1. INTRODUCTION

Creative thought is the process by which individuals and groups advance society, whether through incremental changes to existing technologies, or through innovations that change the perceived limitations of systems. Developing a better understanding of the cognitive mechanisms of creativity supports the creative process, e.g., through development of more effective tools and methods for innovation (Cagan, 2007). Furthermore, it has been argued that any credible theory of creativity must be consistent with a modern understanding of brain function (Pfenninger & Shubik, 2001). We are thus motivated towards a better understanding of the cognitive and neurological mechanisms involved in creativity.

Research from cognitive psychology, which aims to model and describe human thought processes, is clearly applicable to the design process. Cognitive theories have long been applied to develop design tools. For instance, design techniques that encourage a more distributed thought process, e.g., brainstorming or the use of random stimuli, are shaped by Mednick's (1962) theory on the associative basis of creativity. Cognitive theories have also been used to develop computer software capable of simulating creativity (Boden, 1998). In addition to cognitive psychology, we also draw from research in neuroscience, the study of the nervous system, to develop a model of creativity and explain creative phenomena.

The goals of this paper are to:

1) Establish that a theoretical-neurological model based on long-term potentiation can accurately explain creativity phenomena relevant to design.
2) Describe how this theory could be applied towards enhancing the creative design process.
3) Discuss the results of a study that tested one application of the theory, highlighting key methodological challenges.

We first outline the relevant psychological and neurological literature related to creativity, with an emphasis on long-term potentiation (LTP). LTP is an increase in the efficiency of synaptic connections between neurons, due to their repeated and synchronous firing. Next, we discuss the role of LTP in creativity and potential applications of our LTP-based model to enhance creativity.

2. LITERATURE REVIEW SCOPE

Motivating our work is an initial literature review that identified a gap in the biological explanations of creativity. While multiple biological models of creativity exist, there is little work explaining how mechanisms of neural plasticity such as LTP are involved in the generation of creative thought. However, the likely role of LTP in memory formation (Bliss & Collingridge, 1993) as well as learning (Cline, 1998; Van-Pragg et al. 1999) suggest as a logical extension, the role of LTP in creative cognition, a process that involves both.

Cognitive psychology provides ample research that aims to describe the creative process. Particularly relevant are connectionist and associative theories that explain cognitive processes in terms of connectivity and the spread of activation between neurons or groups of neurons. Research on creativity in cognitive psychology often involves problem-solving paradigms, making it more easily transferable to engineering design than research from other fields in psychology.

The literature review was further refined by the desire to provide a biological explanation of creativity. To understand the cognitive mechanisms that enable creativity, priority was given to the internal processes involved and not external measures of them. Explaining the neurological process of creativity requires an understanding of the mechanics of information processing in the brain, a primary focus of cognitive neuroscience. Psychology textbooks were also referenced to provide a fundamental basis.

3. BACKGROUND: BIOLOGY AND PSYCHOLOGY

Background on neural biology follows to clarify the role of LTP in the communication of information in the brain. Connectionist and associative theories of creativity are then reviewed to highlight how changing connection strengths in a neural network influence creative thought.

3.1. Neural Biology

Psychologists (MacDougall, 1905; Perky, 1910) have studied creativity as a distinct cognitive process since the early 1900's, and work on creativity has since grown exponentially. However, Jung et al. (2009) report that there has been little advancement in developing a neuro-biological explanation of creativity until the turn of the 21st century.

Previous neuro-biological research focused on attributing creativity to specific brain regions. Martindale (1999), among others (Heilman et al. 2003), proposed that the right side of the brain is responsible for generating creative thought. Dietrich (2004) put forth a model describing the role of specific neural circuits in creativity, with the pre-frontal cortex as an executive component in the generation of creative thought. Other biological models are based on connectionist theories of cognition. For example, Gabora (2010) proposes a neurological model of creativity in which "atypical" neural structures are activated during creative thought, in turn allowing individuals to form new connections between concepts, resulting in novel thoughts.

Such research is compelling and has strong explanatory power regarding the outcome of creative processes. However, the role of LTP as a mechanism by which connections in the brain can be altered, and the effect of LTP on the creative process has received little attention in the literature. Although Lippin (2001) credited Greenberg, an evolutionary biologist, for supporting LTP as a likely biological mechanism involved in creativity, no detailed explanation is provided. Others discussed the influence of neural plasticity on creativity (Haier, 1993; Heilman et al. 2003), but did not directly implicate LTP. Yet, LTP plays a role in mediating the connection strength between neurons and directly influences the spread of activation in a neural network. To preface why neural connections and the spread of activation between them are important for creative cognition, a background on neural transmission and connectionist theory follows.

3.1.1. Neural transmission. A basic understanding of how the human brain transmits information is needed to understand how LTP could influence creativity. We provide an overview below adapted from Breedlove et al. (2007a).

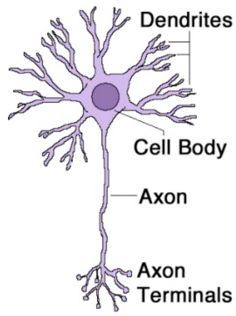

Figure 1: Typical Neuron (adapted from Breedlove et al. 2007a)

The brain is composed of billions of interconnected processing units called *neurons* (Figures 1 & 2). <u>Neurons</u> are the basic cellular unit of the nervous system, and transmit information through electric and chemical signals. Within a neuron, an electric signal transmitted is called an <u>action potential</u>. The action potential is generated when a neuron's membrane potential is altered in a process called *depolarization*. <u>Depolarization</u> results from the flow of ions in and out of the cell body, and if the resultant membrane potential of the neuron exceeds its threshold level (~ -55 mV) an *action potential* is generated. The action potential is ionically propagated from the cell body, down the axon to the *axon terminals*. <u>Axon terminals</u> are structures that form *synaptic* connections with other neurons, and contain *synaptic vesicles* with various <u>neurotransmitters</u>, molecules that chemically signal changes in neurons. The arrival of the action potential at the axon terminals triggers the release of neurotransmitters, which diffuse into the <u>synapse</u>, the gap between one neuron's axon and another's dendrites, where they bond with receptors on the post-synaptic neuron (Figure 2). <u>Dendrites</u> are also extensions of the neuron's cell body, but unlike axons, are specialised to receive signals from other neurons. <u>Receptors</u> are structures on dendrites that only bind with specific neurotransmitters, and produce specific responses in the post-synaptic neuron upon successful binding. Based on the receptor characteristics of the post-synaptic neuron, and the neurotransmitters released by the pre-synaptic neuron, the post-synaptic neuron may or may not achieve enough depolarization to generate an action potential and continue propagating the signal. Neuron physiology is variable, and there are multiple types of neurons and transmitters, so there are more complicated ways in which action potentials can be propagated. However this rudimentary explanation is sufficient for our purposes.

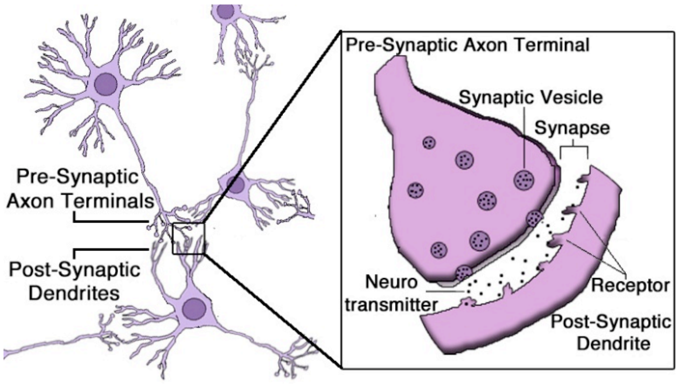

Figure 2: A network of neurons (left) with an enlarged view of a synaptic connection (right). The synaptic connection is adapted from http://scienceblogs.com.

3.1.2. Long-term potentiation. Bliss et al. (2003) provide the following description of LTP:

> In LTP, the strength of synapses between neurons in the central nervous system is potentiated for prolonged periods following brief but intense synaptic activation (pp. 607).

More simply, neurons that are activated together can become more efficient in communicating information. Breedlove et al. (2007b) outline how these changes in connectivity are possible based on alterations in neurotransmitter release, receptor characteristics, synapse size, or changes in enzymes that modulate neurotransmitters. LTP may also be the result of changes to neuronal structure, e.g., increased proliferation of dendrites, and the number of synapses between neurons. Short-term potentiation (STP) is another term used to describe more rapidly occurring potentiation that subsides quickly, i.e., 5-20 minutes (Malenka & Nicoll, 1999). Since the effect of LTP and STP on neural connectivity is similar, for simplicity, we will use the term LTP to refer to both in this paper.

LTP has received considerable empirical support. Bliss & Lomo (1973) and Bliss & Gardner-Medwin (1973) obtained evidence of LTP when they documented long-lasting changes in the neurons of rabbits after externally stimulating large groups of neurons. This research demonstrated that external stimulation of neurons could result in an increase in the synaptic efficiency between them, even after the stimulation was removed. Further research revealed that LTP was not limited to instances in which neurons were stimulated artificially. Thompson et al. (1983) demonstrated that LTP occurred in rabbits induced to exhibit a conditioned eye-blink response. They were able to electrophysiologically measure a change in synaptic efficiency between neurons in response to the rabbits' behavioural conditioning. Teyler & DiScenna (1987) provide additional examples of how behavioural conditioning can lead to LTP. Because LTP results from behavioural change in response to external stimuli, it is not surprising Bliss & Collingridge (1993) implicated it as a possible mechanism of human memory. For a comprehensive explanation of the role of LTP in memory refer to Martin et al. (2000). Cline (1998) and Van-Pragg et al. (1999) also suggested LTP as a mechanism involved in the learning process. Therefore, it stands to reason that LTP could be involved in creative cognition as well.

3.2. Connectionist Models of Creativity

Martindale (1995) provided two reasons to consider connectionist models when developing a cognitive theory: 1) these models unify multiple psychological theories, and 2) relevant to LTP's creativity role, connectionist theory parallels theories based on biological information processing networks.

Fodor & Pylyshyn (1988) describe connectionist systems as networks comprised of simple, but highly interconnected processing units. The terminology for these units varies, but will be consistently referred to in this paper as "nodes." Fodor & Pylyshyn (1998) further note there are various levels of connection strength between nodes in the network, and the connection strengths and input activation at each node determine how information is transmitted through the system. Because connectionist theories are meant to describe cognitive processes, these nodes can represent individual neurons, or assemblages of neurons that encode a mental construct. Donald Hebb (1949) was an early, if not the original, proponent of connectionist theory. He proposed that neurons that fired together would become more efficient information processing units. For example, if an input entering the system triggers node A to fire, and node A firing causes node B to fire, the connection between the two nodes may become more efficient. This theory was later supported by research demonstrating LTP, which provided a biological explanation for how neural connection strength could be altered.

Connectionist models allow for changing connection strengths, which is important, as this in turn allows for *adaptability* in response to stimulus input. Adaptability is required to develop a biological model of creativity because a static model does not accurately describe the process of human creativity. Designers working to develop a creative solution for a given problem must integrate information in novel ways to generate new ideas. Therefore, any model that accurately describes the creative process must allow for the processing of information in new ways. The robustness of connectionist networks is evident in the work of Cleermans (1993), who provides an overview of how computer programs based on these networks have the capacity to learn. Because LTP can alter the connection strength between neurons and groups of neurons, it is possible that LTP is the mechanism through which changes in connectionist networks occur.

3.2.1. Associative creativity. Associative models of creativity are reviewed to further highlight the importance of changing connection strengths and the spread of neural activation in the creative process. Mednick (1962) proposed a model of creativity based on associative hierarchies composed of various nodes that represent an individual's knowledge. The activation of any one node will, by association, lead to the activation of others in the hierarchy. The example used to illustrate this concept is that by providing the hierarchy with the input ”table”, other nodes in the mental hierarchy related to ”table”, such as “chair” and “dinner”, are also activated. Creativity in this model depends on how the different nodes are associated, and Mednick (1962) proposed that a greater number of associations between nodes increased the probability of reaching a creative solution.

Spreading activation theory describes a model for searching associative networks (Quillian, 1962; Collins & Loftus, 1975) that can be used to predict which associations are most likely to form. This theory proposes that as a network is searched, activation will spread from the starting point outwards, directed by the connection strength between each set of nodes. Activation spreads out along strong connections and is resisted at weak connections. Parallel distributed processing (PDP) models of cognition can also be used to describe the spread of activation in a connectionist network, and more details on these models are provided by Rumelhart et al. (1986). Because LTP can alter the connectivity between nodes in a neural network, it can also influence the spread of activation and the formation of associations.

Despite support for the idea that a more distributed mode of thought, or wider spread of activation, may lead to a greater diversity of ideas, diversity does not necessarily lead to enhanced creativity. In engineering design, and to a varying degree in psychology research (see Dietrich, 2004; Dijksterhuis & Meurs, 2006 for an example of the variability), the creativity of an idea depends on both its novelty, and its appropriateness given the problem requirements (Amabile, 1983). Gabora (2010) developed an associative hierarchical model accounting for this, incorporating distributed and focused activation. Gabora (2010) proposes that distributed and associative activation in the network is responsible for generating original ideas, but more analytical or focused activation in the network is responsible for developing the feasibility of these ideas.

Since the connections between nodes dictate the distribution of activation in the network, understanding how the connections are altered is the next logical step. This highlights the importance of LTP in creativity.

4. LTP AND CREATIVITY

The existence of LTP reveals that the brain can rewire itself due to repeated patterns of neural activity. According to connectionist and associative theories of creativity, alterations in the connection between nodes of the network will alter the spread of activation across it. The extent of the spread of activation in the network dictates both the novelty and appropriateness of creative thoughts (Gabora, 2010). Since LTP mediates this distribution, it likely influences creative cognition. Next, we discuss LTP in the context of creativity phenomena relevant to design.

4.1. Fixation in Design

Jansson & Smith (1991) refer to fixation as “a blind, and sometimes counterproductive, adherence to a limited set of ideas in the design process.” Often, fixation is the result of previous experience. Duncker (1945) observed that individuals who saw a box used as a container were less likely to use it for other purposes, e.g., a platform for standing. This phenomenon is referred to as functional fixedness, and is defined by German & Barrett (2005) as difficulty in considering an item for a function other than the one for which it is typically used. Functional fixedness has even been observed in technologically sparse cultures. German & Barrett (2005) demonstrated functional fixedness in an Ecuadorian tribe that had been primed with the function of an item to which it had not been previously exposed. Being primed with the function of an unknown item limited subsequent manners of use of that item.

In other instances, fixation is induced by exposure to stimuli presented during the problem solving process. Dijksterhuis & Meurs (2006), Jansson & Smith (1991), Linsey et al. (2010), and Perttula & Liikkanen (2006), all demonstrated that presenting example design solutions can induce fixation. In these cases, designers typically generate ideas that share elements with the example solution. For instance, Linsey et al. (2010) detected fixation in participants by comparing how similar the ideas they generated were to a provided example. Essentially, fixation limits a designer’s ability to generate novel thoughts, because they tend to think congruently with presented stimuli or previous experience.

Adding to fixation’s negative influence on novel idea generation, individuals are typically unaware they are fixated (Marsh et al. 1999). Linsey et al. (2010) revealed that even experienced designers succumb to fixation without realizing it. Metcalfe (1986) demonstrated that individuals are often unaware when they are engaged in an ineffective problem solving strategy. Because fixation occurs without designers’ awareness, it could be the result of some unconscious and automatic bias in human information processing.

4.1.1. The causal role of LTP in fixation. To explain how fixation could be the result of LTP, fixation should be thought of as: *An automatic cognitive process, in which the generation of novel ideas is inhibited or biased by the dominance of a limited set of stimuli, which influence the distribution of neural activity in a neural network.* In terms of the previously described associative model of creativity, fixation occurs when certain nodes and connection strengths in the network prevent the spread of activation to nodes required for novel associations. This hinders creativity, since creative solutions require the formation of new connections between concepts. Fixation can be considered as the inability to activate new nodes that are not strongly associated with the fixating information. This view is consistent with Ward’s (1994; 1995) theory of Structured Imagination and Path of Least Resistance. Ward proposes that during the generation of novel ideas, central attributes of the novel concept will be determined based on the frequency they are associated with known representations of similar concepts. In this way, exposure to existing concepts biases the development of new ones, which is exactly what is observed during fixation.

Since LTP alters the connectivity between nodes, it can be used to explain fixation. Groups of neurons that are frequently activated together develop stronger, more efficient connections. As a result, it is difficult for activation to spread to nodes that are infrequently associated with the fixation target. For example, in functional fixedness, repeated use of an object for a specific function reinforces the connection between the concept of the object and its typical use. This simultaneously makes it less likely activation will spread to a set of nodes that would lead to novel usage of the object.

Bliss et al. (2003) reported that even brief stimulation of neurons can lead to LTP. In fact, Malenka & Nicoll (1999) asserted LTP could be triggered in seconds. Since LTP can develop quickly, it can explain fixation that results from brief exposure to fixating stimuli in design. The presentation of an example solution immediately activates neural pathways linked to nodes in the brain responsible for internal representations of the stimuli. As the designer begins to think about solutions to the problem, the generation of new ideas is influenced by the example stimuli because, due to LTP, nodes and connections related to the stimuli are more efficient.

4.1.2. Fixation in experts. LTP can also be used to explain why fixation occurs in experienced designers. Because experts have acquired a large body of knowledge related to their domain, their neural architecture has a wide array of neural networks relevant to the problem task. This can make experts more efficient problem solvers. However, when generating creative ideas, solutions to problems often require individuals to think beyond their current knowledge base, and experts often have difficulty doing this. Chase & Simon (1973) found that experts' problem solving is hindered when a solution requires approaching a problem with a perspective incompatible with the domain of expertise. Mednick (1962) suggests that experts have steep associative hierarchies around ideas in their field of expertise, making it difficult for them to think unconventionally. LTP is a possible mechanism that allows connections between well-learned information to dominate a neural network. Experts may become fixated because their neural networks have many nodes with strong connections to certain concepts within their expertise, making it difficult for them to make new, unconventional associations.

4.1.3. Fixation is not permanent. It may appear that the role of LTP in creativity predicts that individuals risk becoming permanently fixated, as network connections become progressively more efficient. This, fortunately, is far from true. While LTP is described as a long lasting change, it is not necessarily a permanent one. In fact, Bliss et al. (2003) assert that the duration of LTP is still unknown. Therefore, an increased efficiency between two connections in the neural network could eventually weaken. Also, a neural network is constantly bombarded with information that activates different nodes, resulting in the continuous formation of new connections that will influence how activation spreads. There are also billions of connections in a neural network, which probabilistically limits the likelihood any one group of connections will permanently dominate. Finally, since the distribution of activation over the network is influenced by how an individual allocates their attention, the distribution of activity in the network can be consciously moderated.

A caveat is that incoming stimuli are often interpreted based on existing cognitive biases. For example, if there is strong activation of nodes A, B and C, the presentation of a stimuli that activates node D may cause node D to connect to the A, B, and C path. In this way, pre-existing networks could still bias the formation of new ones, which explains the persistence of functional fixedness and fixation.

4.1.4. Enhancing awareness of fixation. If designers can be made aware that they are fixated, they may be more likely to avoid continuing on an unproductive path. An obvious approach for detecting fixation may be to directly measure LTP, or look for highly active neural paths. However, this process would be physiologically invasive or require neural imaging techniques. Difficulties in isolating specific regions implicated in fixation on specific problem attributes, if such regions exist, further complicate the process. It is therefore unlikely that directly detecting LTP to enhance awareness of fixation is a practical solution. Nevertheless, in neural transmission, a repeating pattern of activation likely indicates an area of fixation. A proxy measure could therefore be used to demonstrate this repetition of activation.

Bliss & Collingridge (1993) suggest that LTP is a possible mechanism for memory formation. Since repeated activation of connections leads to LTP, and LTP is implicated in memory and possibly fixation, a memory task may be useful to detect fixation. Information that is highly active and strongly connected to multiple concepts in a neural network will be easier to recall. By testing an individual's memory for problem-relevant information at any stage of the design process, the accuracy of his or her memory may be used to identify areas of fixation. An individual will likely have better memory for information that is strongly active in their neural network, and this information may be involved in fixation.

4.1.5. How to use memory to detect fixation. If an individual generates a map of problem-relevant attributes, they are essentially generating a rudimentary externalization of their internal neural network. If an individual generates one externalization and then attempts to regenerate it at a later time, identifying overlap between the two externalizations may reflect regions of fixation. Conversely, information that does not overlap may be useful to focus on, as it may reduce the effect of fixation by exploring weaker connections.

Applying connectionist theory, externalized maps could take the form of a network of nodes representing problem attributes. Gero's (1990) function-structure-behaviour categories could serve as initial nodes in an externalization. Another possible externalizing technique developed by Linsey (2007) is the WordTree method, which involves the generation of linguistic problem descriptors. It may seem promising to have designers externalize problem strategies, since researchers suggested that problem strategies are forgotten during incubation (Simon, 1966; Smith & Blankenship, 1989). However, as Metcalfe (1986) points out, individuals have difficulty realizing they are engaged in inefficient problem solving strategies, which may lead to difficulty in formally externalizing such problem strategies.

Although possible externalization techniques exist, further research is required to determine how to best apply these techniques to detect fixation. In addition, statistical testing is required to determine the degree of overlap between two externalizations that is indicative of fixation, and not just average memory performance. Finally, overlap between any externalizations regardless of the content may not always indicate inefficient problem solving, since fixating on problem-relevant information may lead to appropriate solutions. However, if little progress is being made, this method may be used to identify potential areas of fixation that are inhibiting creativity.

A possible benefit of externalizing problem-relevant information to detect fixation is that the process involves taking a break from actively working on the problem, which reduces fixation. However, there is also a risk that repeatedly externalizing fixated material further reinforces fixation.

4.2. Unconscious Processing and Incubation

In Wallas' (1926) stages of creativity, incubation is described as a phase when an individual stops consciously working on a problem, after which insight and enhanced problem solving occur spontaneously. Wagner et al. (2004) demonstrated that sleep could inspire insight, further supporting the notion that unconscious processing could enhance creativity. Biological models have also been used to explain the role of unconscious processing. Dietrich (2004) suggests that reduced control over thought from the pre-frontal cortex allows for "spontaneous thought" that is less restricted by cognitive biases. Substantial evidence supports that stepping away from a problem, and not consciously thinking about it, is associated with defixation and enhanced creativity. However, Smith & Blankenship (1989) suggest that the actual role of incubation is that it allows individuals to forget ineffective cues that block an effective problem solution, and not the unconscious processing of problem-relevant information. Similarly, Simon (1966) argues that during incubation, individuals forget the problem strategies they were using to interpret problem-relevant information.

Incubation effects can be explained by LTP in a neural network model of creativity. Because the duration of LTP is not definite (Malenka & Nicoll, 1999; Bliss et al. 2003), when individuals are not consciously directing attention to the problem during the incubation phase, potentiation between previously activated nodes may subside. A potential problem arises if the nodes involved in conscious thought are the same nodes active in unconscious thought. If they were, unconscious processes would be biased in the same way as conscious ones. However, Dietrich (2004) suggests that non-deliberate or spontaneous processing, e.g., daydreaming, involves distinct neural circuitry separate from deliberate processing. This allows for the existence of two, somewhat segregated neural networks.

Given the relationship between LTP and memory, it is likely that the incubation process weakens the strength of connections related to inefficient problem strategies or information. Subsequent illumination would be the result of the development of new and unrelated connections.

4.3. Design by Analogy

Many researchers in engineering design exploit the use of analogies to enhance creativity (Casakin & Goldschmidt, 1999; Christensen & Schunn, 2007; Linsey et al. 2010; Perttula & Liikkanen, 2006; Tseng et al. 2008). One benefit of analogies is that they may induce *isomorphic* problem solving. Two problems are isomorphic when they have the same fundamental structure but differ in content (Sternberg, 2009). For example, Mak & Shu (2008) describe the application of biological analogies to solve engineering problems, where the biological phenomenon and the engineering problem share a similar underlying structure, but differ in superficial content. The similarity in structure allows designers to extrapolate from one domain to another, leading to enhanced problem solving and creativity. This section will explore the role of LTP in the design-by-analogy process.

4.3.1. Shortcomings of analogy. The use of analogy does not always result in successful problem solving. Individuals are unlikely to detect isomorphism when surface characteristics of the problem and analogy are extremely different (Sternberg, 2009). Gick & Holyoak (1980) revealed that when an analogy was not explicitly identified as relevant, fewer individuals used it to solve a given problem. Therefore, even if a designer is exposed to a helpful analogy, it may not result in enhanced problem solving and creativity.

4.3.2. LTP and analogy. Biased processing may explain failures in selecting, recognizing and applying analogies. Applying connectionist theory and LTP, individuals' processing of information is directed along strongly connected neural pathways. Analogies congruent with the current activation structure in a neural network will seem more relevant to the designer, and will more likely be selected. The application of analogies will be similarly biased, since strong existing neural connections would lead the individual to map the analogy, or elements of it, in ways that are consistent with existing cognitive biases, as well as design solutions already developed. This is consistent with Mak and Shu's (2008) observation. These biases are partially governed by the strength of connections between nodes in the neural network. If the analogy does not trigger any of the strongly activated nodes, the individual will be unlikely to perceive it as relevant.

4.3.3. Assistive Artificial Networks. Developing techniques to support individuals in selecting relevant analogies, free from their existing biases will support design by analogy. This is more difficult than it may seem, since it requires cognitive processing without referencing biased networks, in a system guided by processing using those networks. The most obvious solution involves externalizing the process. To avoid relying on a third party, this could be done using artificial intelligence and assistive computer software. Bohm et al. (2005) suggest that design repositories can be used to provide designers access to a large body of knowledge beyond their own experience, assisting with innovation. Kurtoglu et al. (2009) demonstrated that computer generated design aids can in fact enhance performance in an idea generation task.

A potential challenge that should be considered in the development of these systems is that the information the individual inputs and extracts from the system will be biased. If the software provides possible analogies, it is important that the software, and not the designer, determines the order, importance, or relevance of the analogies. Otherwise the designer is likely to attend only to the analogies that are congruent with their current pattern of biased thought, which will obviously not promote the most effective activation of new and creative networks. This behaviour has been observed in design using biological analogies (Shu, 2010).

Another challenge is that individuals may be quick to dismiss the validity of a system that provides examples that appear irrelevant. Therefore, the individual using the software must also be trained to avoid bias in their interaction with it.

4.4. Teams

Contradictory findings regarding the creativity of teams (Paulus, 2000) may be explained by considering the involvement of LTP and neural networks. It is possible that when ideas are shared in a group, the contribution from one individual immediately begins to bias the thoughts of others in a similar direction. However, having multiple individuals present divergent ideas may support the spread of activation in novel ways leading to new associations for each individual. Also, each individual in the group possesses a unique neural network, and may be able to interpret the ideas of group members in entirely new ways. Therefore, the best way to enhance group creativity is to allow individuals to generate and interpret ideas free from the group's biases. Ideas should be shared in such a way as to limit the biases of one designer being passed on to others, while allowing each individual to contribute freely.

Techniques such as 6-3-5 and C-sketch exist to facilitate this kind of interaction. Briefly, Otto and Wood (2001) describe 6-3-5 as a method where 6 individuals, each with a sheet of paper, generate 3 ideas every 5 minutes. After 5 minutes each individual's sheet is passed around until every group member has contributed 3 ideas to each sheet. The C-sketch technique is similar, however it involves generating pictorial sketches instead of using words to describe ideas. Shah et al. (2001) found that using the C-sketch method led to more novel idea generation than 6-3-5. This result was attributed to the fact that with sketches, there was a greater likelihood that one group member would misinterpret an idea generated by another. Benami and Jin (2002) also found that when problem-relevant information is provided in an ambiguous form, the number of solutions generated increases. These findings support that being able to interpret other group members' ideas freely could lead to enhanced group creativity. Individuals may interpret ambiguous information in line with their own biases, but when that information becomes explicit, they may become more heavily biased in thinking similarly to other group members. This may also explain the ineffectiveness of brainstorming techniques (Amabile, 1996, pp. 244-245) that simply instruct group members to generate as many ideas as possible without judgement. According to the current proposal, encouraging ideas to be shared somewhat ambiguously is just as important as restricting judgement.

A possible approach to increase the benefit of teamwork is to develop methods to visualize and share problem-relevant information in unbiased ways. If teams can interact and modify representations of group members' problem solutions, it may be possible to more quickly identify both fixations and novel ideas. Sketching problem solutions may be more effective than using words, if it is conducive to novel interpretation. Promising future applications of this theory may be in the development of software that would facilitate "representations" of neural networks that could be shared between group members.

4.5. Physical Activity

In a review of the effects of physical activity on cognitive function, Kramer et al. (2006) found that exercise is associated with enhanced cognitive processes such as planning, working-memory, focused attention, and multi-tasking. They also found that the most significant benefits occurred with aerobic exercise. In addition, physical activity is associated with improved brain plasticity, decreased neuroatrophy and enhanced LTP (Van-Pragg et al. 1999; Cotman & Berchtold, 2002; Farmer et al. 2004). The benefits of exercise on cognitive processes supports the exploration of how exercise could be used to enhance creativity.

If fixation is the result of LTP, it is possible that physical activity could worsen the effect if it strengthens neural connections responsible for fixation. However, engaging in physical activity often takes the individual out of an environment that is perpetuating the fixation. Furthermore, if physical activity enhances LTP, it may also support defixation by strengthening connections that are unrelated to the fixation material. Therefore, an application of this effect may be in the design of active defixation strategies. Performing a physical activity concurrently with a task unrelated to the problem may enhance LTP in pathways that are not associated with the fixation stimuli. It is also possible that changing contexts from a design problem to physical activity would alter the neural architecture to reduce fixation itself, so long as the problem is not being thought about during the physical activity. Designers should therefore consider incorporating physical activity into defixation strategies, or into the design process itself to limit the potential onset of fixation.

5. STUDY: FIXATION & PHYSICAL ACTIVITY

The role of LTP in the creative process is currently theoretical. Validation of this theory will require experimental testing. We report the results of a study conducted to examine the relationship between fixation and physical activity.

5.1. Methods and Procedure

Twenty-four University of Toronto students (16 males, 8 females) participated in the study. Participants were asked to design a watering system for a houseplant that would administer 1/10th of a litre of water per week (adapted from Perttula & Liikkanen, 2006). Participants were provided with an example solution meant to induce fixation and given 10 minutes to generate as many solutions to the problem as possible. They then performed 10 minutes of defixation activity, followed by another 10 minutes of idea generation.

Participants were randomly assigned to one of two conditions, a defixation task involving physical activity, or the same defixation task without physical activity. The defixation task involved reading a short story written in Swedish with English translations. Participants were instructed to memorize the content of the story and the English translations of the Swedish phrases. In the physical defixation condition, participants were required perform a step-aerobic activity, adjacent to the workstation, while performing the language defixation task. In the no-physical activity condition, participants performed the language task, while seated at the workstation.

Fixation was rated by three independent judges based on the similarity of participants' solutions to the example solution. Similarity was rated along 4 dimensions identified by Perttula and Liikkanen (2006): 1) water source, 2) regulation of flow, 3) water transfer, and 4) energy source. A fixation score for each idea was generated which reflected the number of elements the problem solution shared with the example. Next, a participant's average fixation score was calculated for all of the ideas generated in each condition, resulting in a score between 0 (no-fixation) and 1 (complete fixation). The requirements for the evaluation of fixation were adapted from Amabile's (1996, Chap. 3) Consensual Assessment Technique for evaluating creativity. Judges: 1) were selected who had familiarity with the domain, 2) made their assessments independently, and 3) viewed the design solutions in random order. The design task provided also conforms to guidelines outlined by Amabile (1996, Chap. 3) for evaluating creativity, mainly the task: 1) produces a clearly observable product and 2) allows for flexibility in responses.

5.2. Results

5.2.1. Fixation rating. Fixation was scored in 122 design solutions by three independent judges. The reliability of the fixation measure was assessed using intra-class correlation for the scores from two randomly selected judges. The reliability of the measure was statistically significant, $ICC(3,1) = 0.660$, $F = 5.23$, $p < .001$.

5.2.2. Physical activity. A 2X2 (Physical Activity: Yes, No) X (Defixation: Before, After) repeated measures ANOVA was used to examine the effect of physical activity on fixation. There was no significant interaction between defixation and physical activity, $F(1,22) = 0.18$, $p > .05$. Participants' mean fixation scores were lower after the defixation activity than before, however this result was not statistically significant, $F(1,22) = 3.04$, $p > 0.05$. There was no significant effect of physical activity, $F(1,22) = 0.03$, $p > 0.05$.

5.2.3. Follow-up analysis. The sample used in this study consisted of 15 engineers (14 males, 1 female) and 9 non-engineers (7 females, 2 males), roughly balanced across conditions. The previous repeated measures analysis (5.2.2.) was repeated including engineering education (Yes, No) as a covariate. A significant effect of engineering education was found, $F(1,21) = 5.82$, $p < 0.05$. Non-engineers were less fixated overall ($M = 0.41$, $SD = 0.21$) than engineers ($M = 0.63$, $SD = 0.23$). This effect was qualified by a significant interaction between engineering education and defixation $F(1,21) = 4.90$, $p < 0.05$ (see Figure 3). Paired samples t-tests were used to compare the effect of the defixation activity for engineers and non-engineers separately. Non-engineers' fixation scores were significantly lower, $t(9) = 3.38$, $p = 0.01$, after the defixation activity than before (*Mean Difference* = 0.16). However, engineers' defixation scores did not change significantly, $t(14) = 0.12$, $p > 0.05$, (Mean Difference = 0.01).

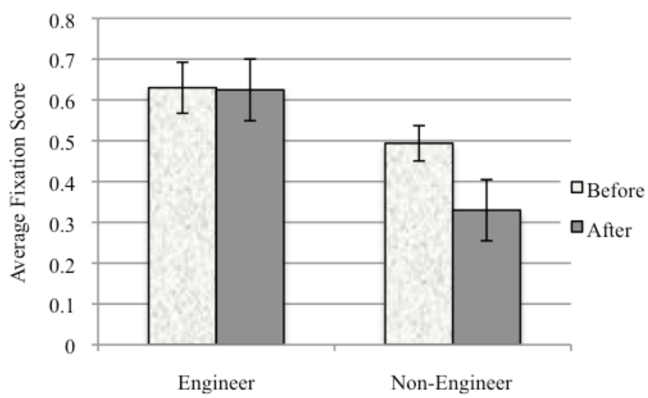

Figure 3: Mean fixation score by education.

The difference between engineers and non-engineers warranted the examination of the engineers' data separately. A 2X2 (Physical Activity: Yes, No) X (Defixation: Before, After) repeated measures ANOVA was performed with the number of solutions engineering participants generated as the dependent variable. No significant effect of the defixation activity was found $F(1,13) = 1.68$, $p > .05$. However, there was a significant effect of physical activity, $F(1,13) = 5.65$, $p < .05$, and a marginally significant interaction $F(1,13) = 4.25$, $p = .06$ (see Figure 4). Engineers in the physical activity condition tended to generate more solutions after defixation ($M = 3.38$, $SD = 0.74$) than before ($M = 2.75$, SD = 1.04). Conversely engineers in the no physical activity condition tended to generate fewer solutions after defixation ($M = 2.00$, $SD = 0.82$) than before ($M = 2.14$, $SD = 0.90$). A paired-samples t-test revealed engineers in the physical activity condition generated significantly more solutions after defixation than before $t(7) = 2.38$, $p < .05$.

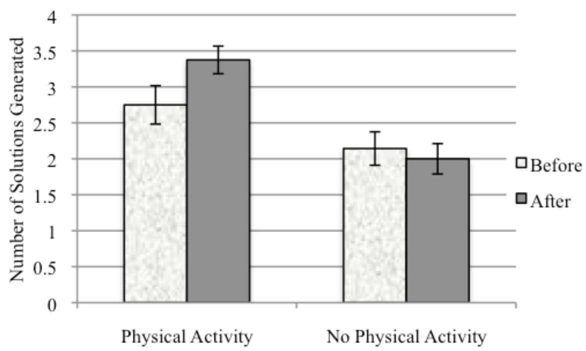

Figure 4: Mean number of solutions by condition.

5.3. Discussion

5.3.1. Group differences. Amabile (1996, Chap. 3) suggests the influence of individual differences on creativity assessment can be minimized if the creative task does not rely overly on specific skills. Although we were unable to identify a significant effect of physical activity on defixation, further analysis revealed significant differences in fixation scores between engineers and non-engineers. Engineering education was included as a covariate in our analysis and accounted for significant variability in fixation scores. Therefore, this variable is important to consider in future research on fixation.

The finding that the defixation activity led to decreased fixation for non-engineers, but not engineers, has implications for the LTP explanation of fixation. Engineers' training may increase the strength of neural connections relating to specific solution strategies. LTP would make it more difficult to encourage the spread of activation through alternate paths for individuals whose pre-existing paths are strongly connected. This finding is consistent with research showing experts have difficulty generating solutions that are incompatible with their domain of expertise (Chase & Simon, 1973). It also suggests that it is easier to defixate individuals lacking domain-specific expertise relevant to the problem.

5.3.2. Measuring fixation. Several concerns raised during data analysis revealed methodological challenges in the assessment of fixation. Although the intraclass correlation was significant, judges did disagree over the fixation ratings for many concepts. The design task was structured to allow participants flexibility in the solution process, however many participants' solutions were ambiguous regarding the fixation categories being scored. For example, participants often indicated that a reservoir would serve as a water source, however they did not specify how the reservoir would be filled. This idea may be rated as partially fixated (0.5/1.0) if the judge assumes the reservoir is filled from a residential water line (the example source). However, it would be rated as unfixated if the reservoir was filled with a different source, e.g., collected rainwater. To increase consistency between judges, the design task should be structured to eliminate ambiguity regarding the fixation categories. Encouraging participants to focus on developing complete solutions, or discarding ambiguous solutions, would increase consistency.

5.3.3. Physical activity. The limited aerobic exertion and limited duration of exercise (10 minutes) may have contributed to the lack of an effect of physical activity. Participants were asked to step up and down from an aerobic step block, set at 6 inches high, at a brisk and consistent pace. However, participant physiological measures, e.g., heart rate, were not recorded and we cannot account for variability in the aerobic exertion actually experienced. In addition, studies showing the effect of physical activity on LTP involve longer durations and more intense activity. For example, Van-Pragg et al. (1999) observed their effect in mice that ran an average of 4.78 km per day for 30 days. The ten minutes of exercise in this study may not have been enough to result in LTP between neurons recruited for the defixation activity.

5.3.4. Assessing creativity. The data was analyzed to test the hypothesis that physical activity helps individuals defixate. However, the creativity of participant solutions was not directly rated. The judges noted that some problem solutions shared common elements, even though they did not share them with the example stimuli, e.g., participants repeatedly using a reservoir as a water source. While not indicative of fixation on the given example, this reveals the participant was generating fewer original ideas. Also, many participants generated solutions that failed to conform to the problem requirements, e.g., suggesting a gardener be hired to water the plant. Measures of creativity accounting for feasibility and appropriateness could be used to test whether physical activity contributes to enhanced creativity.

5.3.5. Number of solutions. Physical activity had a significant effect on the number of solutions generated by engineers. In addition, subjective reports revealed that individuals in the physical activity condition found generating solutions became easier after defixation than did participants in the no physical activity condition. However, generating more solutions did not equal generating less fixated solutions. This result parallels findings regarding the traditional brainstorming technique. Although brainstorming tends to lead to an increase in the quantity of ideas generated, it does not contribute to increased idea quality (Stein, 1975). Similarly in this study, there was no strong relationship between the number of solutions participants generated and the quality of those solutions. Still, these results suggest that physical activity did have an effect on the problem solving process.

An important challenge for future fixation studies is to accurately quantify fixation in a way that is not biased by solution quantity. Reinig et al. (2007) identify 4 metrics for assessing the quality of ideation: 1) *Number*: the number of ideas generated, 2) *Sum of Quality*: the summed quality of ideas, 3) *Average Quality*: the average quality of ideas, or 4) *Good Idea Count*: the number of ideas generated that exceed a threshold quality. Using reliability analysis, Reinig et al. (2007) determined that of the four methods, only good idea count was a valid measure of idea quality. However, they acknowledge that this method ignores the number of poor ideas generated as well as variance in the quality of good ideas.

6. SUMMARY AND CONCLUSIONS

We assert that creativity is biased by the efficiency of connections in the brain, and that the efficiency of these connections is subject to change based on experience through LTP. Previous research aimed to explain creativity at different levels of abstraction, from the influence of environmental factors, to localizing creativity to physical structures in the brain. However, previous research does not explain how biological mechanisms that allow for flexibility in the connections between nodes in a neural network could influence creativity. The theory proposed in this paper posits LTP as the mechanism by which the connections between neurons become more efficient, which in turn leads to biased thought processes dictated by strongly connected pathways. This theory can be applied to explain many phenomena relevant to design, including fixation, incubation, challenges in design-by-analogy, as well as group creativity.

We propose that LTP modulating activation over a neural network will influence creativity, and that this could inform the development of methods and tools to improve the creative design process.

We suggest that to avoid or remedy fixation, one should:

1) Identify non-overlapping areas in externalized neural networks and focus on developing them further.
2) Develop assistive technologies, e.g., software, that compensate for user biases in the input and extraction of information, possibly by identifying areas indicative of fixation and providing more novel stimuli.
3) When working in teams, share ideas in an unbiased or ambiguous way. This will enhance team members' contribution to the novelty of ideas generated.

This theory can also be applied to the development of new metrics to increase awareness of fixation. Promising practical methods for achieving this include externalizing problem-relevant information and quantifying levels of fixation based on familiarity and memory.

Contrary to anecdotal evidence and intuitive expectation, an initial experimental study did not reveal statistically significant effects of physical exercise on defixation. While methodological challenges were identified that may have limited the ability of the study to detect the expected effects, other interesting results were discovered and discussed.

This paper provides a neurological explanation for numerous phenomena and identifies a promising new area for research to enhance creativity in design. In addition, the role of LTP in creativity may become more relevant as techniques of modulating LTP are developed. The desire to understand the neurology of creativity is reason alone to justify further research. However, the application of this theory has clear potential for immediate, practical improvements to engineering-design and problem-solving processes.

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