Creative states: A cognitive neuroscience approach to understanding and improving creativity in design

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The aim of the present paper is to discuss recent evidence from cognitive psychology and cognitive neuroscience that bear on the cognitive and neural processes underlying creative production. The paper will review factors that may obstruct idea generation in creative design and will discuss instructional approaches with the potential to support the resolution of such obstacles. Specifically, the issues of fixation to pictorial examples, as well as functional fixedness in object use during creative problem solving, will be addressed. Furthermore, the paper will examine the hypothesis that creative generation might benefit from a tradeoff in neural activity between anterior and posterior brain regions. Within this context, evidence from cognitive neuroscience that points to distinct brain areas implicated in non-creative and creative tasks will be presented. The paper will conclude by considering creativity as the ability for prospective thinking and perspective taking and the implications of such a definition for creative design.

Introduction: Creativity as a topic of scientific inquiry

In *The Principles of Psychology* William James argued, “Genius… means little more than the faculty of perceiving in an unhabitual way” (1890, *The Principles of Psychology*, vol. 2, p. 110). Since then, the topic of creative innovation—of breaking away from established ways of thinking to generate something new—has been of interest for generations of psychologists and educators. However, despite its high societal value, the scientific study of creativity has been far from the forefront of psychological research, largely due to the difficulties associated with the definition and criteria for creativity and the theoretical and methodological shortcomings of early attempts to study creative production in the laboratory [1].

Among the common misconceptions regarding creativity—that have likely undermined its status as a topic of scientific inquiry in psychology—is the view that creative products come about as the result of extraordinary abilities that are possessed only by a group of selected individuals [2]. In this paper, I will embrace an alternative position: that creative innovations are based on the individual's past experience and are the product of ordinary thought processes, such as memory, problem solving, imagining, and analogical reasoning; these cognitive tools are available to everyone and serve as the basis for all creative achievements [3], [4], [5]. Critically, these cognitive processes can be studied in the laboratory using established scientific methodologies, thus allowing one to determine cause-and-effect relationships regarding creative thought.

Another commonly held position about creativity is that novel products must be deemed valuable within their respective field to be considered creative [6]. However, for the scientific study of creativity it is important to differentiate between the novelty and the value of the creative product. Although novelty can be defined as the generation of an idea or product that a person has not produced before, value is defined relative to current social and historical circumstances, hence its definition can change over time [2], [7]. This means that, if our operational definitions of creativity include the notion of value, then a product that is considered creative today, may not be considered creative ten years from now, and vice versa (consider, for instance, that Egas Moniz received the Nobel Prize in Physiology and Medicine in 1949 for the invention of the prefrontal lobotomy, a procedure universally condemned today as inhumane; in contrast, the modernist painting *Nude Descending a Staircase N⁰ 2* by Marcel Duchamp is currently considered a modern art classic, yet was vastly rejected in its time). Accordingly, any conclusions drawn from experimental studies on creativity that confound novelty and value would not be generalizable to future creative acts. For these reasons, although acknowledging the pragmatic significance of the question of value for novel products, the research discussed here will examine creativity independently of the societal value of the creative product.

Finally, although creativity is frequently defined within the context of a specific domain (e.g., in the arts, music, literature, or science), in this paper I will define creativity more broadly as the goal-directed process of intentionally producing something novel that a given individual has not produced before. Notwithstanding that creative achievement is the result of a complex set of factors, including personal history, motivation, and personality characteristics, I will focus here on the cognitive processes underlying creative thought and their possible neural underpinnings.

Within this context, the research from cognitive psychology and cognitive neuroscience that will be presented in this paper has the potential to inform our understanding of creativity in many disciplines and could be applicable to investigators from a range of backgrounds and perspectives. Given the focus of this workshop on visual and spatial creativity, however, I will discuss findings that pertain more closely to creative generation in design. Specifically, I will present research that (a) can promote our understanding of the cognitive processes implicated in design creativity and (b) may support educational efforts to foster creative production in design. These issues will be addressed in more detail in the following section.

Creativity in design

Similar to the definition of creativity, the definition of design can take on different meanings for different individuals, depending on their focus on the design process or the design product. For the purposes of this paper, design refers to the cognitive process of generating and manipulating representations involved in solving a design problem within a given context and range of constraints [8], [9], [10], [11]. In particular, during the design process, a designer (e.g., engineer, architect, product designer) uses his or her expert knowledge (e.g., of dimensions, appropriateness of style and materials) to generate and evaluate ideas toward the achievement of a goal (e.g., build a computer interface, design an ecologically-friendly apartment building, generate a new travel mug), within a range of constraints (e.g., budget, space availability, client needs). As such, the design process involves a complex interplay between knowledge-driven or goal-driven (top-down) thinking and environmentally-driven or data-driven (bottom-up) thinking. Balancing *how* and *when* a designer moves from one end of this continuum to the other may predict his or her success in solving a design problem both creatively and efficiently [8].

Psychological studies of the creative process can illuminate the factors that determine a designer's flexibility in negotiating—on the one hand—their knowledge, past experience, and understanding of the design objectives, and—on the other hand—the need to come up with a design solution that is innovative and unique. Specifically with regards to the question of creativity in design problem solving, certain aspects of one's knowledge and experience may at times actually impede creative thought. At the same time, the generation of ideas that do not take into account design goals and constraints may undermine the designer's success in reaching a viable design solution.

Within this context, this paper will first review certain factors related to an individual's experience and knowledge organization that can impede creative idea generation and then discuss different techniques that have proven successful in addressing such constraints to creative thought. The following sections will further explore the hypothesis that the extent to which an individual uses their knowledge and experience during problem solving is associated with distinct patterns of brain activity that reveal a tradeoff between anterior prefrontal regions (typically involved in higher-order cognitive processing) and posterior, occipital-temporal regions (typically involved in visual object processing). Finally, based on evidence from cognitive neuroscience, the paper will offer the proposal that success in creative design is based on the designers' ability for prospective thinking and perspective taking—two cognitive processes that may allow good designers to predict the consequences of their design decisions and the audience's response to the newly-created products.

Design fixation: Effects of pictorial examples on creative generation

Without doubt, one's knowledge and experience with certain kinds of problems or situations can support their attempts to solve a new problem that shares similar characteristics with the past. This phenomenon in problem solving is defined as *analogical transfer* and its positive effects have been well-documented in the literature [12], [13]. On the other hand, analogical transfer does not always promote successful solutions; in fact, reaching the solution to an earlier problem may have negative effects on current problem-solving attempts [14]. An example of such negative transfer is known as *functional fixedness* or *fixation* to a particular problem solving strategy that may not be useful in a current problem-solving situation [15], [16].

Functional fixedness is particularly pertinent to discussions of creative design due to its possible detrimental effects to the generation of creative design solutions. Of relevance to design education, in particular, is the phenomenon of fixation to pictorial examples during problem solving. Smith, Ward, and Schumacher [17], for instance, asked participants to imagine and create designs of different categories (e.g., animals to inhabit a foreign planet). In one of their conditions, participants were presented with pictorial examples prior to the design phase. Those subjects who were presented with the examples tended to reproduce in their sketches elements of the example designs, compared to subjects who were not shown such examples.

Fixation to pictorial examples has been specifically documented in the domain of engineering design [18], [19], [20]. Jansson and Smith [18] administered to engineering design students and professionals different design problems with the task to generate as many design solutions as possible. Although the total number of designs produced was similar, participants who had received example designs with the problems tended to conform to the elements of the example design significantly more so than participants who were not exposed to such examples. Critically, the effect did not diminish either when participants were given detailed descriptions emphasizing the negative characteristics of the example design, or when subjects were explicitly told to avoid replicating the examples. Interestingly, professional designers were not immune to this effect: they showed levels of fixation to examples that were comparable to engineering design students.

Purcell and Gero [19] examined in more detail the role of experience in a designer's susceptibility to fixation. They used a comprehensive coding methodology to examine the phenomenon across different designer disciplines and levels of expertise. Their findings replicated those of earlier research [18], though only for disciplines for which the example designs were characterized by an increased level of complexity (e.g., mechanical engineering). Based on these results, it is possible that the occurrence of fixation is determined by an interaction between a designer's discipline and the degree of complexity of the example design that may impose increased attentional demands on the designers.

The consequences of functional fixedness are critical for creative design. However, is design fixation observed exclusively in professional designers [21]? Or is it a broader cognitive phenomenon affecting design experts and novices alike? Moreover, are there instructional techniques that can be used effectively to eliminate design fixation?

In two experiments, Chrysikou and Weisberg [22] examined the occurrence of fixation to pictorial examples in participants who were naïve to design tasks. The participants were assigned to three conditions: (a) control (standard instructions), (b) fixation (inclusion of a problematic example, accompanied by description of its elements, including problematic elements), and (c) defixation (inclusion of a problematic example, accompanied by instructions to avoid using its problematic elements). Importantly, in contrast to prior work, participants were tested individually in a controlled laboratory setting. Participants saw multiple design problems during the session and were asked to generate as many ideas as they could for each, as well as draw sketches of their solutions and elaborate on their designs with brief comments. In addition, they were asked to read the task instructions aloud to ensure that they had reviewed and understood them in their entirety. Critically, in Experiment 1 participants were instructed to ‘think aloud’ during problem solving, so that a record of their thought processes could be obtained [23], whereas in Experiment 2 participants solved the problems silently.

Quantitative analyses focused on measures of design fixation as employed in previous work [19]. These included (a) measures of similarity (direct, reproductive, and analogical), (b) measures of reproduction of intentional flaws, and (c) measures of unintentional flaws. Moreover, to examine in detail the extent to which participants in each condition followed the examples, participants’ verbal responses were transcribed and analyzed qualitatively by statement and for each problem separately. In particular, each statement was assigned to one of 10 categories, adapted from prior research [24]: (1) using the problem instructions to implement a step; (2) using the example to implement a step; (3) using the problem instructions to repair an impasse; (4) using the example to repair an impasse; (5) using the problem instructions to check an action or a decision; (6) using the example to check an action or a decision; (7) following the example; (8) personal reference; (9) interaction with the experimenter; and (10) miscellaneous [22]. Two independent raters coded all responses on both quantitative and qualitative measures with high inter-rater agreement.

With respect to the quantitative measures, participants in the fixation condition in Experiment 1 produced significantly more elements of the example in their solutions and included more intentional and unintentional flaws in their designs relative to participants in the control condition. Importantly, however, participants in the defixation condition were able to thwart the deleterious effects of pictorial examples and their performance did not differ from the control condition. The qualitative results mirrored the pattern of the quantitative findings. Experiment 2, for which participants did not think aloud, replicated the quantitative results of Experiment 1; that is, the inclusion of the example design produced strong fixation effects; however, explicit instructions to avoid using the features presented in the examples also eliminated the fixation effect.

Overall, research on design fixation suggests that naïve participants and experts alike are susceptible to the effects of negative transfer in design problem solving. Strikingly, participants tend to fixate on pictorial examples and reproduce their elements, even in cases where the examples are explicitly described as problematic [18], [19], [22]. However, when participants attend to the defixation instructions in a controlled laboratory setting, they can successfully prevent the deleterious effects of the examples on the creative generation process.

Pictures and words as stimuli in open-ended tasks

The findings discussed in the previous section have demonstrated that pictorial examples can be an obstacle to creativity in design problem solving. A question that arises from this research is whether design fixation occurs only under specific circumstances, within the context of specific types of problems. In other words, are certain types of problem solving tasks more susceptible to functional fixedness from pictorial stimuli than others?

Problem solving, in general, (and design problem solving in particular) refers to a situation in which the individual develops and implements plans with the intention of moving from a problem state to a goal state, within a range of constraints [2]. Some problems are well-defined or close-ended; for those, both the goal to be achieved and the path to be followed for the solution are obvious and the problem is perceived as having one correct answer (e.g., solving the equation 220 × 3 = ?). In contrast, other problems are ill-defined or open-ended; for those, the goal and the steps necessary for its completion are open to interpretation and the solution possibilities appear infinite. Consider, for instance Duncker's candle problem [15], a classic example from the problem solving literature: *Your goal is to attach a candle to a wall so that it can burn upright. You have available a candle, a book of matches and a box of tacks. How would you solve the problem?* The problem is vague and can have an infinite number of solutions (with the 'correct' one being to rethink or re-categorize the box of thumbtacks not as a container for the tacks but as a platform, tack it to the wall and place the candle on the top).

Based on the findings from the design fixation literature as reviewed above, it is possible that the effects of pictorial stimuli are particularly strong for open-ended tasks (i.e., when multiple solutions are possible, e.g., designing a GPS system for the disabled), but are not equally present when the task is close-ended (i.e., when there is one correct answer, e.g., calculating the dimensions of a ceiling beam). In a recent study, Chrysikou and colleagues [25] explored this hypothesis by asking college students to respond verbally to one of three tasks that varied on this close- to open-ended dimension: (a) generate the typical use for a set of everyday objects; (b) generate a common alternative use for a different set of objects; and (c) generate an uncommon use for another set of objects. Critically, a third of the subjects were shown words as stimuli, a third of the subjects were shown pictures as stimuli, and the remaining third were shown both the word and the picture for each object.

Participants' verbal onset reaction times were recorded for quantitative analysis. In addition, their responses were transcribed and analyzed qualitatively with the use of a novel categorization system that categorized participants' answers for each object and task on a continuum from conceptually-driven to perceptually-driven responses. Specifically, conceptually-driven responses were used to describe typical object functions (e.g., chair: to sit on) or functions that substituted the object for another tool based on shared abstract properties (i.e., properties not visible or available without prior knowledge of what the object is; e.g., hairdryer: to blow leaves). In contrast, perceptually-driven responses were used to describe functions that substituted the object for another tool based on shared perceptual properties (i.e., properties visible or available without prior knowledge of the object's identity; e.g., tennis racket: to use as a snow shoe); they further described the generation of a new function for the object based on its perceptual properties (e.g., chair: to use as firewood).

According to the results, although there was no difference in reaction times by stimulus modality, participants who were exposed to the pictorial stimuli, produced significantly *less* perceptually-driven and more conceptually-driven responses than participants who were exposed to the word stimuli; however, this effect was obtained *only* when they performed the open-ended task, that is, when they generated uncommon alternative uses for the objects. Participants who were exposed to a combination of words and pictures did not differ in their responses with either of the other two conditions. These results demonstrate that pictorial stimuli can influence participants' performance in open-ended tasks significantly more so than in close-ended tasks. In particular, the presence of pictures increased the likelihood that participants, when generating uncommon uses for objects, produced uses that conformed to their knowledge of the object's canonical function.

Concepts, categories, goals, and experience

Beyond the effects of stimulus modality as discussed above, our ability to categorize and re-categorize a tool depending on the context is an ability that we all share as goal-oriented beings. This ability is integral to us achieving goals and underlies our proficiency as toolmakers and innovators. What does this ability entail? What are the cognitive systems that allow for this flexible goal-oriented behavior? How can we facilitate optimal goal achievement in everyday problem solving tasks? This section of the paper will focus on the cognitive processes that allow us to employ specific aspects of what we know about an object (or our *semantic knowledge* for that object), as well as how we move beyond our typical interactions with it, to achieve a given goal.

Categorization in problem solving

As mentioned earlier, every problem-solving situation, in which someone is using common objects to achieve a goal, can be described as the result of a continuous interaction between top-down (or knowledge-driven) and bottom-up (or stimulus-driven) processes. For example, if I am out of Styrofoam peanuts and I need to pack a gift, I could start from the goal and then think of ways to satisfy it by examining the properties of the objects around me that could work in that context (e.g., popcorn). Alternatively, I could start from the properties of the objects (e.g., popcorn) and then try to think of goals that they could serve. Although both processes are critical for problem solving, within the context of creative generation it is useful to examine whether one's reliance on preexisting knowledge may impede certain aspects creative problem solving, and whether adopting a bottom-up (feature-driven) mode of thinking can enhance performance on creative generation tasks.

In particular, our long-term knowledge about the world (or our semantic knowledge) has been described in terms of a taxonomic organization, according to which knowledge is organized in distinct, category-specific domains (e.g., birds, mammals, vehicles) [26]. Here, I refer to semantic knowledge as a distributed knowledge system, according to which concepts are distributed across several interconnected domains based on concept attributes or properties (e.g., shape, size, color), that generally correspond to the brain regions originally involved in the acquisition of these properties (e.g., visual cortex for visual information, auditory cortex for acoustic information, and so forth) [27], [28].

Similarly, the term categorization is frequently used to refer to the organization of kinds in taxonomic categories [29]. Here, with the terms categorization or conceptualization I refer to the process of constructing a temporary working memory representation of a category that is derived from our long-term knowledge within a particular context (e.g., construct a working memory representation of the concept 'fruit' within the context of purchasing at the grocery store fruit appropriate for a fruit salad). Accordingly, with the term concept I refer to the temporary construction in working memory that is used to represent a category on a particular occasion (e.g., in the example above, only certain aspects of one's knowledge of fruit, its appropriateness for a fruit salad, would be active in that context) [30], [31], [32], [33].

If our knowledge about the world is organized in categories and concepts in a distributed fashion, how do people dynamically navigate this knowledge to interpret a problem situation and how do they use it to put together a successful strategy toward a goal? To address this question, I have argued that [34]: (1) When people attempt to achieve a goal they activate knowledge that is relevant to the achievement of that goal within that context; and (2) the process of establishing relationships between one's knowledge and the information provided in the problem-solving situation involves numerous categorizations of the elements of a problem according to one's experiences. To clarify this position, consider the following example: a football is typically seen as "a ball with which you score a touchdown." However, seeing a football as "something that floats" becomes particularly relevant when one is drowning in a swimming pool. In contrast, the 'floatability' of the football would most likely not be a particularly salient component of our working representation of it in the middle of a football game [35]. Accordingly, being able to access the right kinds of information from one's knowledge of footballs within each context, may determine their success in using the object successfully to address each goal.

In practice, people can form taxonomic categories about items in the world by learning (and recreating) specific, idiosyncratically-interpreted exemplars from their personal experiences (e.g., fruit, clothes, furniture). Beyond these taxonomic categories, however, in the presence of an impromptu goal, people can construct goal-derived categories through the effortful, mostly top-down, and dynamic process of conceptual combination (e.g., things to sell at a garage sale, ways to make friends, things that can float). These goal-derived categories can be either well-established or ad hoc, depending on one's experience with the particular circumstances [35], [36], [37]. For example, if one is a frequent organizer of barefoot-bohemian-themed parties, the goal-derived category "activities for a barefoot-bohemian-themed party" will be well-established (i.e., it will be easy to instantiate that category with specific exemplars). Importantly, these instantiations can vary widely from individual to individual depending on the context and one's particular experiences (e.g., ways to make friends can mean a very different thing for an incoming and an outgoing president) [35].

Categorization training as a way to improve creativity

With regards to creative problem solving, it is, thus, possible—based on what was discussed above—that success in goal-achievement depends on the individual's ability to break away from well-established categories and construct goal-derived categories, particularly those that are formed ad hoc to serve specific goals. Critically, individuals may differ in their ability to construct these categories depending on (a) whether the task is close-ended (e.g., frying an egg) or open-ended (e.g., constructing a survival kit for natural disasters) and (b) the individual's experiences and how these experiences match a given problem situation. Specifically, if in open-ended tasks the construction of goal-derived categories is critical but difficult to execute, it is likely that training participants to broaden their category boundaries may improve their performance in these tasks.

This hypothesis was examined in two experiments [38]. In the first study, participants were assigned to four conditions depending on the type of training they received: Participants in the Alternative Categories with Critical Items Task (ACT-C) condition generated as many as six alternative categories for 12 common objects. The training task included items critical for the solution to the problems used as dependent measures that were determined after norming (e.g., the tack box, in the Candle Problem). Participants in the Alternative Categories Task (ACT) condition received the ACT task, which was identical to the ACT-C with the difference that none of the objects included were relevant for the solution to the problems that followed (for example a newspaper has nothing to do with the solution to the Candle problem). Participants in the Embedded Figures Test (EFT) condition received the EFT, which was used as a control task to address whether any activity involving "flexible thinking" would work as training. In this task the subject has to identify a simple shape within a complex figure. Finally, participants in the Word Association Test (WA) control condition received as training a simple word association test. Immediately following training, all participants received seven open-ended problems like the Candle problem, all of which required creative problem solving involving everyday objects. Based on earlier research that has shown failure to transfer knowledge from one problem solving situation to another, unless explicitly told to do so [12], [14], for groups ACT, ACT-C, and EFT, participants received specific task instructions regarding the relevance of the training phase to the problem-solving phase.

As predicted, training with the ACT and ACT-C tasks significantly improved problem-solving performance: Participants in these two conditions showed significantly higher proportion of correct solutions relative to participants in the other two conditions, which did not differ from each other. Critically, this effect did not increase with specific training with the items that were crucial for the solution to the presented problems (i.e., in the ACT-C task). These findings were replicated in a second study, which was identical to the first with the exception that participants did not receive explicit instructions regarding the relevance of the pre-problem solving task to the problem-solving phase. In other words, the effect of the training was strong enough to overcome participants' likely tendency to avoid transferring strategies from one task to another without explicit instructions [38].

Overall, these experiments demonstrate that the way people organize and activate their knowledge about the world can determine their success during creative object use. Importantly, they suggest that training people to ‘shake up’ their categories through a brief conceptual exercise can expand their ability to move beyond well-established category boundaries and consider alternative interpretations of the problem elements that can facilitate creative solutions. Although the generalizability of the benefits of this training to other tasks is an empirical question that is currently under investigation, the effectiveness of the ACT task as training—which did not include items relevant to the dependent measures—would hold promise for the use of this procedure to enhance creative generation in a variety of design problem solving tasks.

Creative states: Prefrontal cortex and creativity

Why does asking people to think about concepts more broadly promote problem solving? Is this task—which forces people to challenge traditional category boundaries—associated with a particular neural state? Work in neuroscience has revealed the critical role of the frontal lobes in higher-order cognitive tasks, tasks in which one has to exercise a certain level of cognitive control over available information to achieve optimal performance. Such tasks involve, for example, holding in memory recently-presented information (e.g., the *n*-back task, in which one needs to remember a word or digit presented *n* trials back [39]), rule switching (e.g., the Wisconsin Card Sorting task, in which one has to monitor an implicitly changing rule to sort cards by color, quantity, or shape [40]), or resolving interference from unwanted information (e.g., the Stroop task, in which one is asked to read color words printed in incompatibly-colored ink [41]). The prefrontal cortex (particularly the left ventrolateral prefrontal regions) has also been implicated in tasks that require participants to retrieve information from their knowledge about the world (e.g., retrieving a verb associated with an object or performing similarity judgments among items based on a particular property, like an object’s color or function) [42], [43]. A distinctive feature of all such tasks is that they are close-ended, that is, they require one correct response the form of which is typically known to the participants. However, much of everyday problem solving and, particularly, design problem solving—as discussed above—is open-ended, that is, there is no obvious single response and the tasks seem to have multiple, equally likely solutions. Is the prefrontal cortex implicated similarly in open-ended and close-ended tasks?

Hypofrontality and bottom-up thought

Recent evidence from neuroscience studies involving both normal participants and patient populations would suggest that—in contrast to close-ended tasks—certain aspects of open-ended tasks might benefit from a tradeoff between regions involved in rule-based processing (i.e., prefrontal cortex) and regions involved in object processing, particularly processing of object attributes or features (i.e., visual cortex) [44], [45]. Activity in these distinct brain regions may be associated with different types of thought, namely knowledge-driven or goal-driven (top-down) thinking and environmentally-driven or data-driven (bottom-up) thinking. Specifically, the prefrontal cortex, predominantly in the left hemisphere, may support the construction of rules and regularities about the world that one is *abstracting away* during development from low-level, 'raw' environmental data (e.g., learning that chairs are used for sitting regardless of their shape, size, or color) [46]. In contrast, focusing on low-level, 'raw' perceptual information in the environment (e.g., sounds, shapes, colors, materials) may involve activity in more posterior brain regions (i.e., occipitotemporal cortex). Importantly, depending on the close-ended or open-ended nature of the creative task, an individual may benefit from either top-down or bottom-up thinking for optimal performance, as supported by these distinct brain regions [45].

With regards to creative production, it can be argued that the generation of ideas within the context of an open-ended task (e.g., a creative design task) might involve a temporary distancing from knowledge-driven (top-down) thought—as guided by the prefrontal cortex—and a focus, instead, on data-driven (bottom-up) thought, as supported by posterior brain regions. In fact, evidence from neuroscience would suggest that lower activity in the prefrontal cortex (*hypofrontality*) as the result of disease or injury, may enhance one's ability for bottom-up cognitive processing. For example, patients with progressive aphasia, a neurodegenerative disease that targets selectively the patient's left frontal and temporal cortex, have been reported to exhibit increased levels of visual ability in spontaneous drawing or painting, that they did not possess prior to their disease [48], [49]. Moreover, certain individuals with autism appear to outperform normal participants in reasoning tasks that require acute visual processing. This effect has been attributed to diminished lateral prefrontal cortex function in these individuals, in conjunction with increased brain activity in visual processing (i.e., occipital) regions [49]. Indeed, the suboptimal prefrontal functioning in autism may increase the availability of bottom-up, environmentally-driven information in these patients, which may allow some of them to become musical, mathematical, or artistic savants [50].

Finally, patients with focal strokes in the left prefrontal cortex have been shown to outperform normal participants in creative problem solving tasks that require breaking away from rule-based thinking [51].

The effects of hypofrontal cognitive states on enhanced perceptual processing have also been observed in normal subjects. Specifically, temporarily disrupting left prefrontal cortex activity using rapid transcranial magnetic stimulation (rTMS, a procedure that induces strong magnetic pulses to the scalp, thus altering the activity of underlying brain areas, see Table 1) can improve absolute pitch perception and number estimation in normal subjects [52], [53]. With regards to creative thinking, tasks that require broad conceptual associations have been linked to highly complex electroencephalogram (EEG; see Table 1) patterns across the entire brain, but also reduced activity in frontal brain areas [54]. Finally, a recent study that employed functional magnetic resonance imaging (fMRI; a procedure that allows researchers to acquire images of brain activity while participants perform various cognitive tasks, see Table 1) has shown hypofrontal neural profiles in professional musicians during jazz improvisation, but not during the reproduction of well-practiced musical sequences [55].

Table 1 Neuroscience techniques for the study of creativity

Technique	**Definition**
fMRI	A non-invasive technique that measures changes in blood flow across the brain associated with neural activity during a given cognitive task.
rTMS	A non-invasive procedure that can excite or inhibit neurons in a given brain region after the application of a strong electric current induced through a coil by rapidly changing magnetic fields.
tDCS	A non-invasive procedure involving the application of small currents to the scalp for a few minutes through two surface electrodes that can modulate cortical excitability.
EEG	A non-invasive technique that records the electrical activity across the scalp produced by neural activity in underlying brain regions.

Overall, recent findings from neuroscience would suggest that reduced prefrontal cortex activity may facilitate certain aspects of perceptual processing and can shift the participant’s focus from abstract, knowledge-based thinking to bottom-up, data-driven thinking.

Hypofrontal cognitive states and creative generation

The findings discussed in the sections above would suggest the possibility of distinct neural states associated with top-down and bottom-up thinking. However, does the extent of prefrontal cortical involvement depend on the close-ended or open-ended nature of the task? Importantly, is performance in real-world, open-ended creative generation tasks associated with a distinct hypofrontal neurocognitive state?

A recent neuroimaging study attempted to explore this question and examined—more directly relative to previous work—the link between performance in open-ended, creative generation tasks and diminished prefrontal cortical functioning in normal subjects [56]. It was hypothesized that closed-ended tasks (i.e., having either one or a finite number of possible responses for which the search in conceptual space is deliberate) depend on the controlled retrieval of conceptual memory through the selection of one prepotent response that is facilitated by the left ventrolateral prefrontal cortex. Conversely, open-ended tasks (i.e., having an infinite number of possible responses, for which the search in conceptual space is non-deliberate) rely on the activation of posterior temporal-occipital regions specializing in object attributes or features within a distributed semantic network.

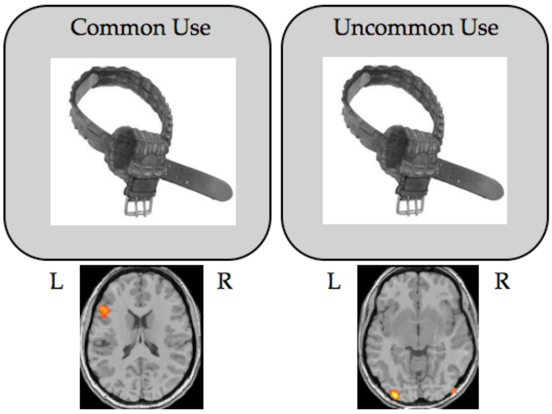

Fig1. Examples of stimuli and corresponding activations in fMRI study [56]

According to this prediction, we combined a close-ended task (i.e., common use generation, e.g., generating for *belt*: to keep one's pants up) and an open-ended task (i.e., uncommon use generation, e.g., generating for *belt*: to use as a tourniquet) in an fMRI paradigm to examine whether these tasks would lead to different types of response generation strategies.

Participants were assigned to one of two conditions, depending on the task they had to perform (i.e., generate common or uncommon uses for everyday objects). They were shown grayscale images of the experimental stimuli and they were asked to generate aloud their responses while in an fMRI scanner. In line with our predictions, participants who generated the common use for everyday objects exhibited increased activity in left lateral prefrontal areas (see Figure 1). In contrast, participants who generated uncommon uses for the objects did not show significant activation in prefrontal regions, but exhibited, instead, increased activation in posterior regions that are typically implicated in visual processing (left fusiform gyrus; see Figure 1). Participants' responses on the uncommon use generation task were further transcribed and coded qualitatively on the continuum from conceptually-driven to perceptually-driven responses, as discussed earlier in this paper (see above, p. 8). These qualitative scores were then correlated with brain activation observed in each participant for an analysis of individual differences. According to the results of this analysis, the more participants' responses were categorized as perceptually based, the higher the activity in the middle occipital gyrus, a region involved in visual perception. This finding possibly reflects increased visual processing during this creative generation task.

In sum, this experiment has provided evidence for a tradeoff between regions involved in the controlled retrieval of conceptual information (i.e., prefrontal cortex) and those implicated in perceptual processing (i.e., posterior occipital regions). Specifically, these results demonstrate that in close-ended tasks, performance relies on the selection of appropriate information as facilitated by the prefrontal cortex; in contrast, in open-ended, creative generation tasks, in which the selection of one prepotent response would be counterproductive, diminished prefrontal cortical functioning, in conjunction with increased perceptual processing, optimizes performance.

Current and future directions

If hypofrontality states are associated with creative generation, is it possible to induce them artificially in normal subjects? As discussed above, rTMS has been used successfully to suppress transiently activity in the left prefrontal cortex, subsequently eliciting savant-like skills in healthy participants [52], [53]. A number of studies involving this procedure are currently underway to investigate the potential of this technique as a neuroenhancement tool for certain types of creative thought. However, rTMS is associated with high costs, difficulty of administration, and certain safety concerns. A different non-invasive procedure that addresses these problems is transcranial direct current stimulation (tDCS, see Table 1). tDCS introduces a brief electric current to the scalp and can modulate the excitability of neurons underlying the locus of stimulation. As such, the technique is currently used to inhibit cortical excitability in prefrontal and other cortical regions and explore the consequences of this modulation for cognitive function in a variety of creative thinking tasks. Although these techniques hold much promise for our understanding of creative cognition, among the aims of current and future research is to explore the magnitude, generalizability, and duration of the observed effects, as well as the effectiveness of these paradigms as interventions for the enhancement of creative thought.

Creativity as prospective thinking and perspective taking

In this paper I have approached creativity broadly as the process of generating something novel that results from the interplay between top-down, goal-driven thinking and bottom-up, data-driven thinking. Specifically, I have presented evidence that bottom-up thinking, as supported by a hypofrontal neural state, can promote the generation of creative ideas. Nevertheless, other aspects of the creative process can significantly benefit from top-down, knowledge-based thought. For example, evaluating design ideas for their appropriateness for a particular audience, or predicting the consequences of one's creative decisions before they are implemented, may determine the success or failure of a creative endeavor. Interestingly, recent work in neuroscience suggests that the human brain is constantly involved in this kind of prospective thought: a specific network of brain regions, including the dorsal prefrontal cortex, is continuously generating predictions about future events that are relevant for a given individual [57]. Critically, this is the same network of regions that is active when people are taking the perspective of another person within a specific context [58]. This ability for prospective thinking and perspective taking may be in the heart of the definition of creativity. Future research should focus on examining the involvement and importance of these brain circuits for our understanding of creative thought.

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