



Review

Creativity on demand – Hacking into creative problem solving

Zsolt Beda^{*}, Steven M. Smith, Joseph Orr

Texas A&M University, United States

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ABSTRACT

How can creative problem solving be enhanced? The paper identifies and examines modulatory approaches from the cognitive and neuroscientific literature that have been made to make creative problem solving better. We review neuromodulatory approaches of both global and local effects. Through a 2-process model of creative problem solving that involves both automatic and controlled processes, we demonstrate how these approaches could be used and what potential they may have for enhancing creative problem solving. We conclude that direct neuromodulation will be best used in unison with behavioral manipulations of cognition, and that better understanding of these manipulations should inform and guide research on direct neuromodulatory procedures.

1. Tools and ways to modulate

How can creative problem solving be enhanced with the tools known to modern neuroscience? People have always wanted to maximize the potential of the human body, to test and surpass the physical and biological limits our bodies represent. Enhancing physical or cognitive capabilities can be as simple as using a screwdriver or an abacus and as complicated as altering neuronal activity in certain areas of the brain with Transcranial Magnetic Stimulation (TMS). We can use tools as extensions to our bodies that make easier tasks, that would otherwise be difficult due to limitations of our physical capabilities. These tools might also help alleviate imperfections that are either present because of genetic reasons or as a result of an accident. Just think of a pair of reading glasses or a prosthetic device. What do the tools of neuroscience add to these enhancement efforts? The ability to directly alter biophysiological processes in our bodies today enables us, for example, to stimulate the spinal cord to speed up or make possible recovery from a serious spinal cord injury that left a patient partially or completely paralyzed (Wagner et al., 2018), or alleviate symptoms of treatment-resistant depression using Deep Brain Stimulation (DBS, e.g., Mayberg et al., 2005). In the following pages we will attempt to put efforts to enhance human creativity into historical perspective, overview the contributions of modern neuroscience to these efforts of enhancement, and suggest how results and knowledge from the pre-neuroscience era might help scientists today to come up with better experimental designs and discoveries. Definitions of the creative process vary a great deal and a review of the entire literature on creative neuroscience would greatly exceed the limitations of this work. There is great research on the neuroscientific background of

artistic creativity (e.g. see Beaty, 2015 for musical improvisation; and Liu et al., 2015 for poetry composition), but for this paper we will concentrate on the field of creative problem solving.

1.1. Cognitive methods

Cognitive and lifestyle techniques aimed to enhance human creative problem solving have existed for thousands of years. They can range from having very general effects - for example a mindfulness training or meditation - to specialized and more local techniques, like direct suppression or even a directed brainstorming session. These cognitive methods mostly use known mental processes to exert a top-down modulation on a different process.

The early history of the study of creative problem solving introduced some important themes that remain relevant today. The two overarching themes to emerge are: 1. The experience of insight (also known as the *aha!* or *Eureka!* moment) is an important phenomenon that can result in unexpected creative ideas (e.g., Köhler, 1925; Wertheimer, 1945), and 2. Creative ideas are difficult to find. The first theme, insight, was a focus of Gestalt psychologists, who also studied fixation, the “archenemy” of insight (Adams, 2001; Duncker, 1945; Luchins and Luchins, 1959; Maier, 1931; Scheerer, 1963). Early studies demonstrated insight using insight problems, that is, puzzle problems that often cause initial failures, followed by cognitive restructuring (i.e., thinking about the problem in a different way) and the experience of insight. The second theme, finding ideas, was addressed both by people interested in applied creative methods for stimulating creativity, and scientists who envisioned finding or combining ideas across a broad representational idea space (e.g.,

^{*} Corresponding author. Department of Psychological and Brain Sciences, 4235 TAMU, Texas A&M University, College Station, TX, 77840., United States.

E-mail addresses: bedazs@tamu.edu (Z. Beda), stevesmith@tamu.edu (S.M. Smith), joseph.orr@tamu.edu (J. Orr).

Newell et al., 1958; Newell and Simon, 1972). One of the most important historic landmarks was the invention of brainstorming (Osborn, 1953), a method in which group members are given an open-ended problem, and they are encouraged to list as many ideas as possible, to include especially wild or free-wheeling ideas, to defer all criticism of ideas until a later time, and to combine and improve ideas whenever possible. Psychometric tests of creativity (Guilford, 1950; Torrance et al., 1966) broke down creative ideation into multiple measures, including fluency (number of ideas), flexibility (number of different categories of ideas), originality, and goodness-of-fit (or quality). The emphasis of brainstorming and psychometric tests on having *many* ideas is characterized by the Darwinian theory of creativity (Campbell, 1960; Simonton, 2011); because most ideas are not creative, a larger pool of ideas has a greater chance of including a creative one. Likewise, travelling farther in a representational idea space confers a greater likelihood of finding a creative idea. Thus, the two basic themes for being more creative are to seek insight by rooting out fixating influences that prevent cognitive restructuring, and to find creative ideas by venturing far afield in one's idea space. We will now consider research that suggests ways of achieving these goals.

1.1.1. Going the distance for creative ideas

Creative ideas might be easy to understand, but they are hard to get. Non-creative ideas are easier to think of, and doing so gets in the way of finding creative ideas. When you find yourself in an unproductive region of idea space, surrounded by non-creative ideas, what ways are there for extracting creative ideas? You can choose to explore more of the same idea space, or “leave” the unproductive region and try to switch to a more, potentially creative one instead.

1.1.1.1. Explore more idea space. We will use Smith's (1995) Roadmaps theory to explain location and movement in an idea space, a theory based in part on Newell and Simon's conception of a problem solving space (Newell et al., 1958; Newell and Simon, 1972). In the theory, ideas are represented as configurations that include multiple features, each of which may or may not be specified. Rough ideas are formed and explored by adding, changing, and removing codes of features in a hierarchically arranged multidimensional idea space. Multiple features (see Fig. 1) of

ideas can be coded (or not coded), with greater specificity lower in the space and greater abstraction at the top. Ideas that are closer to each other are considered to be more closely related, and those that are farther apart are more remote associations. Specification of ideas in this model is easier than abstraction.

For example, given the problem of building a device to travel the greatest possible distance, as described in Fig. 1, a designer might begin with the general and conventional notion of making a vehicle to travel across the surface of land. Sticking to convention, the designer might then think of using wheels to move the vehicle across the land. An automobile may be the conventional choice for a wheeled vehicle, and the designer might opt for a sedan, a specific type of car. Alternatively, the designer could take a less conventional path through their idea space, creating a device to travel through the air, something with a ballistic movement, such as a rocket. Given that the rocket design was the winner in the original competition described by Shah et al. (2003), how can a designer, stuck in the sedan's portion of idea space, find a more creative idea, such as the rocket, which exists in a somewhat distant location in that space?

1.1.1.1.1. Farther is better. One of the best known methods for finding creative ideas is referred to as *Remote Association*, and has been considered by some to be a key ability in creative thinking (e.g., Mednick, 1962). Word association norms (e.g., Bousfield et al., 1954; Thorndike and Lorge, 1944) are associative (or response) hierarchies, each comprised of a rank-ordered frequency tally of responses for a given stimulus word (e.g., CHAIR). The most frequently given response (e.g., table) is referred to as the dominant or pre-potent response, whereas low frequency responses (e.g., toilet or committee) are referred to as remote associates. Individuals can increase the remoteness of their associations, to some degree. In terms of the example shown in Fig. 1, *through the air* is a more remote association for a travel medium than *on land*. Maltzman, Bogartz, and Breger (1958) found that with selective reinforcement of remote associations, originality could be increased. Harkins (2006), investigated potential mediating processes on the Remote Associates Test (RAT, Mednick, 1962) and suggested that the expectation of being evaluated should increase the effort through producing more arousal and therefore will only enhance production of prepotent responses meaning, that this mere effort will only facilitate solutions for easy RAT problems.

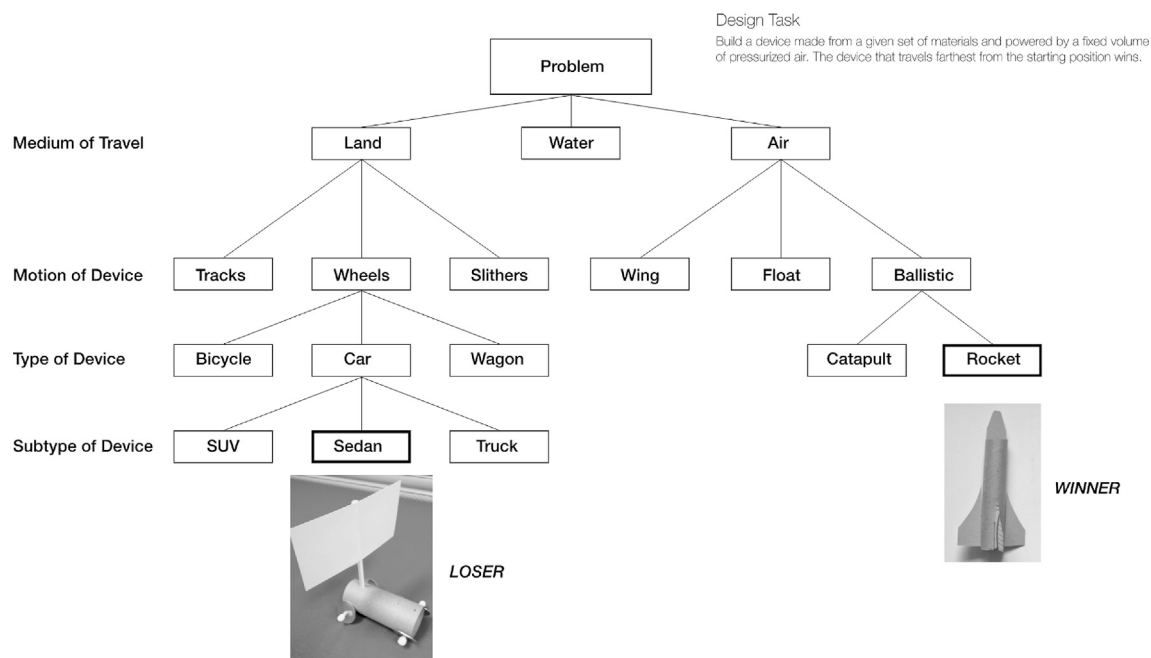


Fig. 1. Hierarchical Idea Space (e.g., Smith, 1995). Features of ideas are coded, with greater specificity lower in the space and greater abstraction at the top. Ideas that are closer are more closely related.

This is not in contrast with the finding of [Martindale \(1995, 1981\)](#), who found that lowered levels of arousal led to more remote associations, as well (these findings were later corroborated by neuroscientific research e.g., [Heilman et al., 2003](#)). There may well be other factors that reliably modulate the remoteness of associations in creative thinking.

The remoteness principle applies not only to verbal associations, but also to analogies. In creative problem solving, scientific discovery, and creative design, people often draw upon analogies, mapping analogical properties and relations from a known domain of knowledge to the problem at hand. The creative use of analogy is likely to be better if retrieved analogies are not restricted to local (i.e., closely related) knowledge; unfortunately, experts retrieve things from their domain of expertise more easily than from more distant domains, a situation known as entrenchment ([Dane, 2010](#)). Linsey and colleagues (e.g., [Linsey et al., 2012, 2008; Smith and Linsey, 2011](#)) have used the method of abstraction, or moving up the idea space “tree” to the point where more distant, but meaningfully related domains can be searched for relevant analogies (see [Fig. 2](#)). Linsey’s method involves the use of a digital tool, Word Tree, to support the designer’s abstraction, enabling a search for a meaningful analogy.

The importance of combinations of ideas for creative new products has been noted as essential since the invention of brainstorming, which identifies combination as essential, because combinations, even of ordinary elements, can lead to creative ideas. Conceptual combination and creativity has been the focus of a great deal of research (e.g., [Estes, 2003; Glucksberg and Estes, 2000; Kohn et al., 2011; Mobley et al., 1992; Mumford et al., 1997; Scott et al., 2005; Wan and Chiu, 2002; Wilkenfeld and Ward, 2001](#)). Combined concepts may be mundane if the features of combinations are simply added together, as in the attribute inheritance model ([Hampton, 1987](#)). When combinations have new and interesting features that are *not* features of either of the combined elements, these special features are referred to as *emergent* qualities because their existence depends on a particular combination of concepts. What makes combinations more likely to have emergent qualities? There is no certain way for producing emergent combinations, but research supports two principles: 1. Combining different, rather than similar elements, and 2. Producing more interpretations of a conceptual combination, rather than few, is more likely to lead to emergent effects (e.g., [Wilkenfeld and Ward, 2001](#)). Thus, combinations of remote ideas, that is, ideas that are more distant from each other in idea space, have a better chance of leading to more original creative ideas.

Another “hack” of creative cognition is to expose someone to various types of external stimuli, sometimes called *provocative stimuli* (e.g., [Shah et al., 2001; Smith et al., 2011](#)). The most commonly studied type of

stimulus is to present a hint or even the solution, itself, in some incidental way. Unsurprisingly, showing people the solution enhances their chances of thinking of the solution (e.g., [Dodds et al., 2002; Moss et al., 2011; Smith et al., 2012; Smith and Blankenship, 1989](#)), but this is not a very helpful creativity hack (because if you already know the solution, why bother with further work?). What types of provocative stimuli, other than hints and solutions, enhance creative thinking? The answer is a bit tricky. A large and growing volume of research on creative design has focused on *design fixation* ([Jansson and Smith, 1991](#)), the tendency to copy features of example ideas in one’s own design attempts, even when the copied features are poor design features and participants are warned to avoid using them (for reviews, see [Sio et al., 2015; Vasconcelos and Crilly, 2016; Youmans and Arciszewski, 2014](#)). Design fixation can be described as drawing ideas from a particular location in idea space, and if the fixated place is limited or problematic, then creative ideation is limited. On the other hand, if the provided examples are creative and original, then designers find themselves in a better part of idea space, ([George et al., 2019](#)). In addition, if designers first try out ideas without the “benefit” of examples, seeing ideas of their peers after those initial attempts can help broaden the idea space explored in more creative designs (e.g., [Shah et al., 2001](#)).

1.1.1.1.2. More is better. Several lines of work of creative thinking, including brainstorming ([Osborn, 1953](#)), psychometric testing (e.g., [Guilford, 1967; Shah et al., 2012; Torrance et al., 1966](#)), and metrics of design ideation ([Shah et al., 2003](#)), endorse the idea that the more ideas that one considers, the more likely it is that a creative idea will be found. A strict Darwinian approach states that blind variation of ideas, followed by selection, eventually produces a creative idea ([Campbell, 1960](#)). Whether or not variation is blind, it is statistically true that more variation is better than less. In terms of idea space, more ideas can mean that more idea space is explored, but of course, that depends on how the space is explored. Nonetheless, it cannot be denied - more attempts clearly produce more successful and creative ideas. The serial order effect, one of the most robust findings in the creative ideation literature, shows that as more responses to a single stimulus are produced, the more original and novel the responses are likely to be ([Christensen et al., 1957](#)). The measure of *fluency*, or number of ideas, as a metric of creative ideation, has been characterized as a process measure, that is, an index of the creative process rather than a measure of creative products, *per se* ([Shah et al., 2003](#)).

One possible reason that prolonged attempts to find creative responses might be successful is that it may increase the opportunity for *mind wandering*, an unstructured drifting of thought that may enable the discovery of unexpected insights (e.g., [Baird et al., 2012; Mooneyham](#)

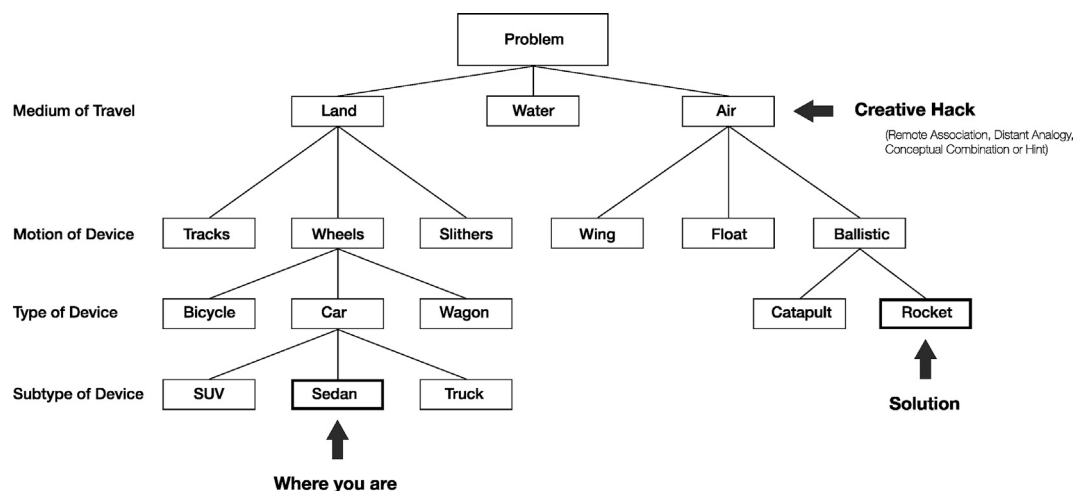


Fig. 2. A creative hack, such as a remote association, a distant analogy, a conceptual combination, or a provocative stimulus can move a fixated search to an unexplored area of idea space.

and Schooler, 2013). Daydreaming and mind wandering are states of mind that are known to go together with an active Default Mode Network (DMN, Mason et al., 2007). (For more on the relationship between daydreaming and creativity, see Zedelius and Schooler, 2016).

1.1.1.1.3. Structured imagination. The structured imagination theory (e.g., Ward, 1994; Ward et al., 1999b, 1995) states that creative ideas are based on pre-existing concepts. Both novices and professionals, for example, include feathers when they create imaginary life forms that fly, and fins for life forms that swim (Ward and Sonneborn, 2009). The theory has many implications for creative thinking, including the use of conceptual combination and conceptual extension to increase the creativity of ideas. One perplexing problem in creative thinking is prematurely settling on an overly-specified idea, rather than exploring other areas of idea space, a problem referred to as thinking along the path of least resistance (Ward et al., 2004, 1999a). For example, design engineers trying to move material over a distance, as in the problem shown in Fig. 1, might first think of a car, and then explore variations of automobiles, rather than thinking more abstractly and broadly about other types of vehicles or modes of conveyance. A *car* is an example of a basic level category (e.g., Murphy, 1982; Rosch, 1978; Rosch et al., 1976), the most general level at which category members have roughly the same shape, and which people of all ages find easy to understand and retrieve. Thus, a consequence of starting one's creative thinking with the idea of a car, in this problem, is that the designer can become fixated, just thinking about various types of automobiles.

Abstraction (see Fig. 3), as previously noted, is a difficult, but effective way to avoid the premature specification of a creative idea. Abstraction might be supplemented by tools such as WordTree, described above. Even without such tools, however, the designer who is fixated with cars might abstract their way out of their rut by asking, for example, “What category of things does *car* belong to? And what other choices belong to that more abstract category?” Asking the same types of questions about the more abstract category, *wheeled vehicles*, for example, and again about *land conveyances*, designers might eventually climb out of the rut enough to realize that devices can travel through a different medium other than by land (see Fig. 3).

1.1.1.2. A fresh look at the problem. Problems that demand creative solutions can make you fixated on wrong or inappropriate ideas if you are unable to shift the way that you think about the problem. For example, in the classic insight problem shown on the left panel of Fig. 4, problem solvers usually think of the problem as determining which 3 circles to move, or how to get the 4 circles from the bottom to the top. Your way of thinking about a problem is an example of a representational structure,

within which you plan to find the solution. Because neither of those mental structures is likely to lead to a solution, this insight problem requires *restructuring*, that is, you have to think about the problem in a different way – which seven circles *do not* change from A to B? A properly restructured representation of a problem may cause a sudden and unexpected insight (or aha! or Eureka!) experience in which the solution flashes to mind (for a summary of neuroscientific research on insight, see Sprugnoli et al., 2017). Such cognitive restructuring can come from taking a fresh look at a problem, analogous to viewing an object from a different perspective (see right panel of Fig. 4). What enhances cognitive restructuring?

One method, well-known by crossword puzzle solvers, is to put a fixated problem momentarily aside; then, the solution may occur suddenly during the break, or upon your return to the puzzle. Such “out-of-the-blue” insights have been called “incubation effects,” suggesting that unconscious processes may be at work during the break (for research on unconscious thinking, see e.g., Dijksterhuis and Meurs, 2006; Dijksterhuis and Nordgren, 2006), but that label might be deceptive in that presently there is no decisive evidence that unconscious processes carry on autonomously during a break. How does an interruption enhance cognitive restructuring? Primarily, it occurs because a break allows you to have a “fresh look” at the problem, seeing it without the fixating ideas that led to your impasse. The *forgetting fixation* theory states that a break in time (e.g., Smith and Blankenship, 1991, 1989) or a change in context (Beda and Smith, 2018; Smith and Beda, 2019; Smith and Beda, 2020) can weaken the retrieval potency of fixating ideas that prevent creative solutions from coming to mind. Thus, our recommended hack is to leave the context associated with your fixation, a recommendation consistent with findings that most people have insights in their everyday lives when they are in places away from the original problem context, such as in the shower, while exercising, driving, or in nature (Ovington et al., 2018).

Another way to diminish the negative effects of fixating material is to suppress it. The benefit of suppression-induced forgetting of pre-potent blockers has been found when blockers were subjected to directed forgetting (Koppel and Storm, 2012) or to think/no-think procedures (Angello et al., 2015).

A lot depends on how people approach a certain task. Instructions to try to think in more abstract ways instead of specifying certain examples will result in more novel ideas (Ward et al., 2004). In the same vain, preliminary instructions to try and disregard potentially constraining or misleading information thus creating more of a *proactive* control environment for identifying misleading intrusions, rather than the *reactive* control we default on, will also bring better results (for more on proactive vs reactive control see the opinion article of Braver, 2012).

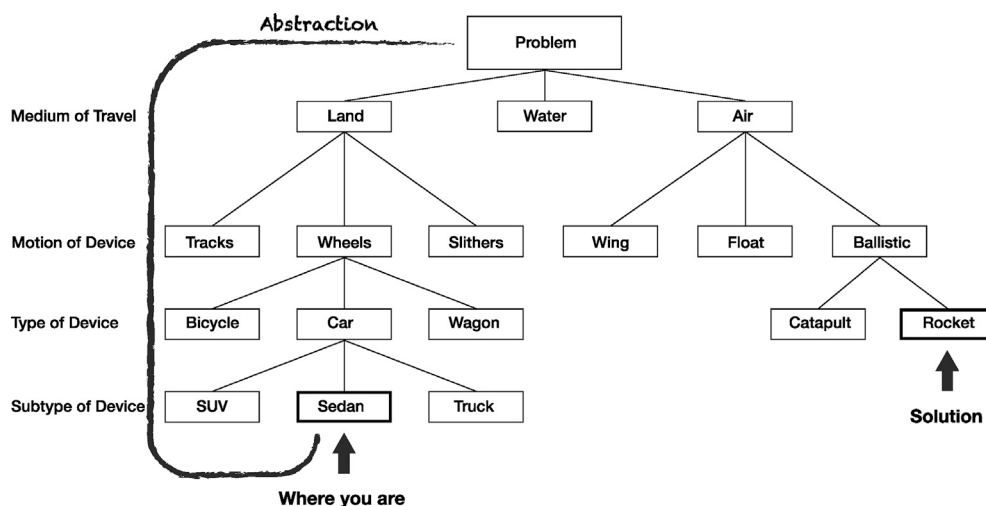


Fig. 3. Premature specification of creative ideas mires the creative problem solver in a restrictive area of idea space. Abstraction is one creative hack that enables escape into other areas of idea space.

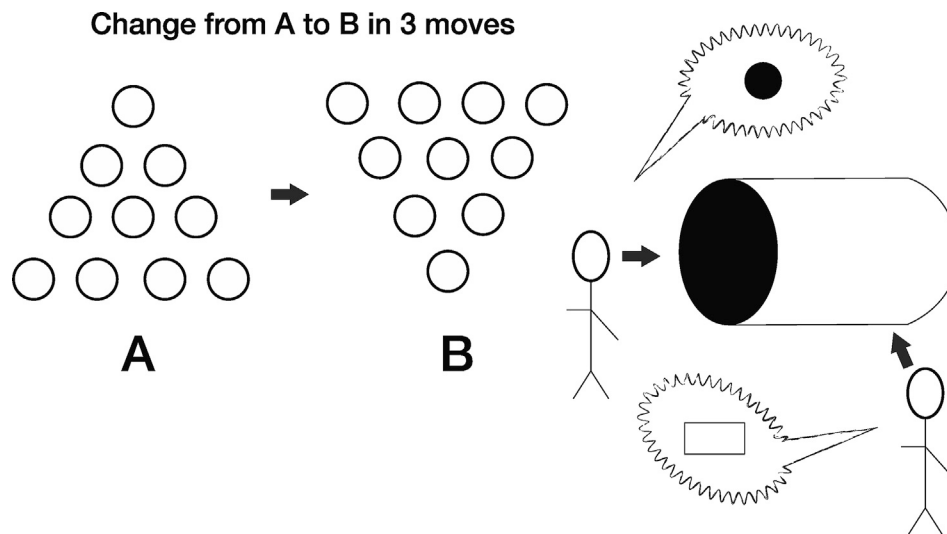


Fig. 4. Maintaining a single perspective on a problem can entrench mental fixation, whereas varied perspectives can lead to creative ideas.

Mood greatly influences a multitude of cognitive processes and it is no different with creative cognition. Creative ideas are reported to come more often when people are in a positive, expansive and open mood (e.g., Isen et al., 1987). One of the hypotheses is that mood acts through modulation of attention or cognitive control in the facilitation of creative processes (Kounios and Beeman, 2014) by increasing the scope of attentional filters thus enabling more remote associations to be included during the search process (Rowe et al., 2007).

Attention in itself is also a crucial element of any thinking process, therefore other ways that positively modulate attention (some commonly mentioned methods would be cognitive attention and mindfulness trainings, meditation, or physical exercise) might also be beneficial from the respect of creative problem solving. There is some research regarding these techniques (Colzato et al., 2017 for effects of meditation, and, Colzato et al., 2013 for effects of physical exercise; Oppezzo and Schwartz, 2014), however, for now they are mostly inconclusive or with weak evidence (Lebuda et al., 2016). Colzato et al. (2012) also suggested that positive mood enhanced by certain meditation techniques might have contributed to the beneficial effects observed in their study.

1.2. Global modulation

The use of available psychoactive or other substances to enhance creative cognition is probably as old as the already mentioned cognitive methods. The common element in how these modulatory methods enhance creative cognition is that a more general effect of a substance or technique exerts collateral benefits for the process to be enhanced. No-tropic compounds are a hot topic as enhancement of mental properties is becoming more desirable in the competitive environment of today.

Mild alcohol intoxication might lower cognitive control and leave creative ideation intact, thus enhancing performance in creative tasks that involve looking for the one possible solution (convergent thinking) from many available alternatives (divergent thinking) as described in two separate studies by Benedek et al. (2017) and Jarosz et al. (2012). Both of these studies used the Remote Associates Test (RAT, Mednick, 1962) to assess creativity before and after alcohol consumption that resulted in the participants getting mildly intoxicated. While Jarosz et al. matched intoxicated and sober participants on working memory capacity before the manipulation, Benedek et al. had a placebo-controlled design and used alcohol-free beer for the control group. Both studies found that mild intoxication somewhat facilitated performance on the Remote Associates Test (RAT), a convergent thinking task, and Benedek et al. additionally found that alcohol did not make a difference in performance at an Alternate Uses Task (AUT), measuring abilities of divergent

thinking.

Alcohol is also thought to decrease our abilities to monitor the accuracy of our responses, therefore might affect our stopping an inaccurate (or intruding) reply. The research article by Campanella et al. (2017) examined neural correlates of response inhibition in alcohol drinkers using a go/no-go task. Their main findings were related to differences in brain activation at failed response inhibition trials between heavy and light drinkers, however, they also documented that the light drinking group did activate the right inferior frontal cortex, thought to be responsible for response inhibition (Chambers et al., 2009) and complementing the previously mentioned creative cognition results (Benedek et al., 2017; Jarosz et al., 2012) they did find creative advantages of mild intoxication.

Tyrosine, an amino acid which is the precursor for dopamine has been assumed to affect cognitive top-down control and thus also enhance convergent thinking (Colzato et al., 2015). Indeed, Colzato and colleagues have found that Tyrosine has facilitated participants' results on the RAT. (The function of dopamine in creative thinking is discussed in more detail in the review paper of Flaherty (2011), who examined changes in the creative thinking of clinical case-studies).

Pharmacological cognitive enhancement (PCE) usually refers to usage of medical substances to improve certain cognitive functions in healthy individuals. Some commonly used examples include methylphenidate, modafinil and mixed amphetamine salts (Schelle et al., 2014), originally developed to treat Attention Deficit Hyperactivity Disorder (ADHD) and Narcolepsy, but used to improve cognitive performance. While several studies examined the potential benefits of these substances on healthy individuals, no solid evidence of enhancements were found (for a meta-analysis, see Repantis et al., 2010).

Looking into psychoactive drugs for the enhancement of creative problem solving tasks intuitively makes sense, but so far there are no real conclusive findings that support this idea. One of the very early attempts in this area was by Oscar Janiger, a psychiatrist at UC Irvine, who administered LSD to over 900 participants between 1954 and 1962, when his experiment was shut down. An interesting finding was about the changes to the quality of the artistic products some of these participants created under the influence of LSD (De Rios and Janiger, 2003). Iszaj et al. (2017) in their review article examined 14 empirical and 5 case studies that focused on relations between psychoactive substances and creativity or creative artistic processes. Due to the diverse methodologies, various substances and study questions they could not adequately summarize results, but concluded that studies were not able to show that usage of these psychoactive substances directly contributed to the enhancement of creative or artistic processes. Rather, the authors

suggested that the substances in question facilitate specific skills like aesthetic experience, problem solving, musical or artistic style and thus might affect creative performance. Results of other such studies are also mostly correlational and some even show the contrary. Kowal et al. (2015) for example found that in regular cannabis users, highly potent cannabis actually impairs convergent thinking, while average strength doses do not cause a statistical difference one way or the other. In a different study of regular cannabis and ecstasy users, more creativity was found in regular cannabis users compared to non-users (no difference between ecstasy users and non-users), but these differences might just show underlying covariates of regular users of a particular drug versus non-users (Jones et al., 2009). A recent study found that cocaine use selectively benefits figural but, in the same time, impairs verbal divergent thinking on the Pattern/Line Meanings Task (Wallach and Kogan, 1965) and AUT respectively (Hutten et al., 2019).

Even though it does not involve any kind of substance, another global type of modulation that could enhance creative thinking as a “side effect” is when the invasive or non-invasive stimulation of the vagus nerve, might create a mental environment that is beneficial for cognitive flexibility through global modulation of the GABAergic system. Colzato et al. (2018) asked their participants to complete tasks of convergent (RAT, Idea Selection Task and Creative Problem Solving Task) and divergent (AUT) thinking following non-invasive transcutaneous vagus nerve stimulation (tVNS). Active stimulation participants compared to sham stimulation participants performed better in fluency and flexibility measures of the divergent thinking tasks, but were no different in the usefulness and originality measures of the same tasks, or the convergent thinking tasks.

Some of the above examples of global manipulation show that there are ways to successfully manipulate some aspects of creative cognition. Results of the alcohol intoxication studies were attributed to lowered levels of inhibition that might affect opportunistic use of hint or cues and might be connected to attentional control (Jarosz et al., 2012). Colzato et al. (2018) hypothesized that tVNS might result in a transient increase in diffuse GABA concentrations in the brain, facilitating selection among competing options under high selection demand, a similar outcome than in the case of alcohol intoxication.

The main issue with a global manipulation in enhancing creative thinking is twofold: first, this kind of a global approach may have undesirable side effects that are hard to control for. Second, this approach is not very informative about cause and effect on the level of cognitive processes, it can basically be regarded as a game of trial and error about what works and what does not.

What would then be a better way to approach successful manipulation of the creative process that would also be informative in a scientific way?

1.3. Local modulation

With neuroscience and the advancement of imaging techniques, our knowledge about the nervous system experienced an exponential growth. Several technologies now exist that can accurately target small, distinct areas of the central nervous system. The highest accuracy in humans is currently achieved by invasive methods, that is, implanting stimulators in the body that connect to the targeted areas with electrodes and use low electric currents to stimulate a group of neurons to change their excitability, or directly make them fire. These implants can target brain areas, as in Deep Brain Stimulation, nerves, as in Vagus Nerve Stimulation (VNS), or the spinal cord, as in Spinal Cord Stimulation (SCS). Optogenetic and chemogenetic methods used in animal studies can directly stimulate cells or groups of cells, but they require either genetically modified cells to express light sensitive ion-channels (in the case of optogenetics), or G-protein-coupled receptors to permit control of G-proteins (in chemogenetics), making them unsuitable to use in humans for the time being.

Non-invasive methods of neuromodulation have been used more

lately and are becoming more accurate. These methods influence neuronal activity by altering the firing thresholds of underlying brain tissue by a magnetic field (TMS), electric current (Transcranial Direct Current Stimulation [tDCS] and Transcutaneous Vagus Nerve Stimulation [tVNS]), or ultrasound (Transcranial Focused Ultrasound Stimulation [tFUS]). The spatial precision of these techniques varies as does the depth of cortical penetration. tDCS is generally restricted to the surface cortex and has a spread that varies considerably depending on the size of the electrodes (as low as 10 cm³ to 50+ cm³). While TMS has greater spatial precision (<10 cm³) with some stimulating coils, the depth of stimulation is generally restricted to the surface. tFUS offers the benefit of high spatial precision and the ability to reach subcortex, but it is a new technology that is not widely available yet.

In the study of creativity, initial efforts of the neuroscientific approach concentrated on finding and describing individual differences, without very consistent results (as expressed in Arden et al., 2010). Simply registering individual differences, however, does little if there is no hope to influence the creative process. Promising attempts have since been made to alter mental activities and enhance the creative process.

Creative thinking is the result of multiple cognitive processes (for a good collection of some, see chapter two in Ward et al., 1995 pp 25–58) which are very intricately intertwined with each other (see conclusions of the meta-analysis by Boccia et al., 2015) and, presently, are poorly understood (Gonen-Yaacovi et al., 2013). It is hard to imagine to successfully manipulate any aspect of creative thinking without first disentangling and dissociating these processes. An important step in the design of an experiment aimed to modulate cognitive functions is to break down these mental processes into their components, identify the component to be modulated and only then attempt the procedure (Dietrich and Kanso, 2010). This componential approach has now more or less become standard practice in the design of neuroscientific experiments.

Chrysikou et al. (2011), for example, used cathodal tDCS on the left and right prefrontal cortex (PFC) along with a sham stimulation. During the stimulation they showed black and white pictures of everyday objects to the participants and asked them to generate common and uncommon uses in a between-subjects design. To control for potential general effects of stimulation, each participant also had to do a forward digit span task, in which they were read increasingly longer number strings and had to repeat them in the order they were presented. They found no difference in the performance on the forward digit span task, but both reaction times and number of responses were facilitated by stimulation on the left PFC when they had to list uncommon uses for the objects. This facilitation meant faster reaction times when the left PFC was stimulated than in the case of the right hemisphere or sham stimulations, as well as more response omissions, when participants could not respond in the allotted time in the case of right hemisphere and sham stimulations than with left hemisphere stimulations. Their results added support to the hypothesis that the lack of top-down regulatory filtering might benefit performance in certain tasks that need more low-level, unfiltered information.

Di Bernardi Luft et al. (2017) hypothesized that inhibition of the dorsolateral prefrontal cortex (dlPFC), implicated in the automatic application of learned rules, would facilitate problem solving that requires relaxation of previously learned rules or constraints. They gave participants 4 different types of matchstick problems both before and after cathodal, anodal or sham stimulation on the left dlPFC. These four types of problems needed differing amounts of constraint relaxation to solve them successfully. In the easiest of the four types requiring the least amount of constraint relaxation only one matchstick was needed to be moved within a specific numeral (for example IV = III + III, where the solution came from moving the I from the left to the right of the V: VI = III + III); in the hardest type, requiring the most constraint relaxation to be solved, for example a stick needed to be slid to make a V out of a X (XI = III + III, solution is VI = III + III). They presented all four types of problems to all participants and claimed to have found that with cathodal stimulation participants were better at solving problems where most

constraint relaxation was needed. Unfortunately, this study showed no results in three of the four types of matchstick problems and the number of participants who could actually solve problems of the fourth type was so low that made the study underpowered.

Hertenstein et al. (2019) applied tDCS bilaterally over the inferior frontal gyrus (IFG) in a between-subjects design, comparing reverse montages and a sham stimulation. They used three different creative tasks to assess performance: the AUT, Compound Remote Associates Task (CRA, Bowden and Jung-Beeman, 2003) and Wisconsin Card Sorting Task (WCST). Compared to sham stimulation, the only improvement they found was on the WCST with cathodal stimulation on the left IFG (anode on the right IFG). They found, however, significant detrimental effects compared to sham stimulation on both solution times of the CRA and performance on the AUT, with the reverse montage.

In a review article Lucchiari et al. (2018) examined 18 studies, that attempted to promote creativity using tDCS. They reached the conclusion that tDCS attempts to enhance creativity did not show consistent results. Another review article by Weinberger et al. (2017) summarized designs for tDCS that so far have yielded enhancements for creative cognition.

The tDCS technique shows promise for the neuromodulation of creativity, however, there are a number of methodological issues that need to be considered when designing a study. These issues have been discussed in great detail elsewhere (Horvath et al., 2014; Woods et al., 2016), so we will briefly summarize them here. In tDCS, 2 or more electrodes are placed on the cap, either within saline/electrolyte-soaked sponges, or in plastic holders filled with electrolyte gel. The size of the electrodes is critical, as increasing electrode size without increasing the current will decrease the current density leading to less current at the site of interest. Another critical methodological consideration is the placement of the 2 electrodes. While the placement of one of the electrodes is generally determined by the region one is interested in stimulating, the placement of the second electrode is often given less consideration. tDCS stimulation involves current passing from the anode electrode to the cathode electrode with tissue underneath each electrode having the highest current density. Therefore, if one places the anode over left dlPFC and the cathode electrode over right dlPFC, both the left and the right dlPFC will receive the highest stimulation, albeit in different directions. It has recently been showed that the effect of prefrontal stimulation on executive function is the largest when the secondary electrode is placed extracranially, e.g., on the back or deltoid (Imburgio and Orr, 2018). This ensures that only one cortical area is stimulated. A third consideration surrounds whether tDCS is applied on-line or concurrently with the task, or whether it is applied off-line. With 10–20 min of stimulation, the after-effects of tDCS continue for about an hour (Woods et al., 2016). Shorter durations of stimulation do not seem to yield after-effects, and only lead to alterations in neurophysiology during stimulation. Therefore, most cognitive studies with tDCS mostly rely on the after-effects and use primarily off-line stimulation. A related technique to tDCS, transcranial alternating current stimulation (tACS), relies on the knowledge that neural communication exists in a series of cortical rhythms. If tACS is applied at the same oscillatory frequency, brain function under the electrodes is increased (Antal and Paulus, 2013). As creativity has been shown to be associated with greater alpha synchronization in frontal brain regions (Fink et al., 2009; Fink and Benedek, 2014; Srinivasan, 2007), frontal alpha tACS seems like a promising method for enhancing creativity.

The above mentioned attempts were all made by locally targeting brain areas that were thought to be responsible for certain elements in the creative process. Even though some of these studies had limited success, they all shared the same element: they used a componential approach to reach their goal.

1.4. The componential approach on an example

Neuroscientific studies on creative cognition are relatively scarce, but the same cognitive processes involved in creativity are also involved in

more basic cognitive domains like memory, executive function and motor planning. The field of creative cognition would benefit from research from these cognitive areas to provide information and assistance during the design of experiments.

Let us present an example of how one could zone in from a general idea of creative cognition into a very elemental subset of a single process and try to break it down into meaningful units where neuromodulation approaches could be used more effectively.

In descriptions of the creative problem solving process in cognitive psychology (e.g., Finke et al., 1992; Smith and Ward, 2012), one common element emerges from the multitude of definitions since Poincaré's lecture at the Société de Psychologie de Paris (see Poincaré, 1910): a creative idea has to be a *novel* use of concepts that are already existing in the individual's mind. (e.g., Beaty and Silvia, 2012; Sawyer, 2012 pg. 7–11) This also naturally implicates one of the biggest obstacles of the creative process: uses of concepts that *already exist* in our minds. Whenever we face a problem that requires a solution never before used by us, our mind seems to be coming up with different alternatives that we are already familiar with (Gilhooly et al., 2007). The process is similar to the formation and automatic usage of habits and skills (see most recent review by Knowlton and Diedrichsen, 2018). If none of these quick, already existing, automatic replies serve as solutions, the ideation process will slow down considerably, as we have to get rid of these intruding notions. This is the element of the creative process on which we choose focus in our example.

These intruding pre-potent alternative, but incorrect solutions have been investigated thoroughly over the years in cognitive psychology and have been variously referred to as *mental fixation* (e.g., Duncker, 1945), *mental set* (Luchins and Luchins, 1959), *cognitive entrenchment* (Dane, 2010), and *red herrings* (Beda and Smith, 2018). During the creative problem solving process, in order to continue working on the solution, we first have to somehow get rid of these obstructing elements. This can be done passively, without any conscious control by simply *forgetting* them, as depicted in the *forgetting fixation theory of incubation effects* (e.g., Smith and Blankenship, 1989). A change of the environment might also bring a new set of pre-potent concepts to mind, where these obstructions are not present anymore, thus paving our way to successful solutions (e.g., Smith and Beda, 2019). Another way to deal with pre-potent blockers in creative problem solving is by active suppression of the intruders, that is, to voluntarily put out of mind these obstructing notions. Directed forgetting has been investigated in the memory literature and the right PFC has been implicated in the process (Aron et al., 2014, 2004). There were also attempts to modulate the directed forgetting process by tDCS (e.g., Silas and Brandt, 2016).

Suppression induced forgetting was demonstrated in the think no-think paradigm (Anderson and Green, 2001), in which participants were instructed to try and not think of the second members of previously memorized word pairs when cued with the first word. As a result, memory of the suppressed words was worse at a final cued-recall test than that of the words they did not have to put out of mind. Using several methods for studying memory inhibition, Storm and colleagues have examined the role of suppression in creative problem solving. Storm and Angello (2010) found that people who showed the greatest retrieval-induced forgetting effects were best at solving RAT problems, suggesting that the individuals who are best at suppressing memories are also best at suppressing competitors of RAT solutions. Storm, Angello, and Bjork (2011) found that trying to think of a common associate to a RAT problem words caused forgetting of other strong associates of those cue words. The problem-solving-induced forgetting effect was positively correlated with performance on a separate set of RAT problems. These results implicate a role for forgetting - memory inhibition - in overcoming fixation in creative problem solving. Consistent with this conclusion are the findings that blockers, themselves, can be effectively suppressed. Koppel and Storm (2012) showed that directed forgetting of blockers reduce the blocking effect, and Angello et al. (2015) showed that blocking was reduced when blockers were repeatedly suppressed. Thus,

the role of pre-potent competitors, and of overcoming such blockers, is centrally important in creative problem solving.

To provide a guideline along which we can discuss ways to modulate this process of creative problem solving, we will propose a chart of how the stages of this particular process follow each other (Fig. 5). As the basis of our proposal, we chose the dual-process model of problem solving. There are indeed other problem solving models such as Kitchener's three process model (Kitchener, 1983), or even more elaborate ones such as the multi-attribute judgment model suggested by Glöckner and Betsch (2008). (For a good collection of these cognitive models in decision making research, see Newell and Bröder, 2008). However, because of its simplicity the dual-process model seemed the most suitable to be used as an example for the componential approach we aim to demonstrate. With this model we will discuss what areas of the brain are depicted in the different mental processes and speculate how each process could be modulated.

2. A dual process model of a creative problem solving process

As a particular problem is presented to us, even while we are trying to understand the nature of it, our brain is already cross-referencing everything with our past experience, looking for patterns or correlations with our past, trying to make sense of it all (Clark, 2013). As a result, a possible solution is getting formulated in our minds as soon as we discover something familiar about the particular problem. This possible solution is a result of an automatic process that also has many names in everyday life: *expertise*, *hunch*, or *intuition* (Kahneman, 2003). In dual-process theory it was simply coined as *System 1* (Stanovich and West, 2000). This automaticity is very fast and provides a shortcut to a solution, so it is very adaptive from an evolutionary point of view. Accordingly, if we want to find the neural correlates of this way of thinking, it would make sense look for deeper, older parts of the brain. From behavioral automaticity studies, the most likely contributor for

these automatic processes in the brain would be the dorsal striatum (e.g., Lipton et al., 2019). The DMN has also been implicated in some habitual, automatic processes by Vatansever et al. (2017), but direct evidence has not been presented to support this theory (for a detailed description of the DMN, see Andrews-Hanna et al., 2014, 2010). The interaction between the executive and DMN areas is thought to be a crucial part in the problem solving process (e.g., Beaty et al., 2019, 2015). It is possible that just like working memory, automatic processes are also domain specific, however, thus far no evidence has been found of neural correlates in this domain (for a review of the domain specificity debate see Camos, 2017).

Of course, it is possible that we have no experience to draw from and we have no real leads to start problem solving. In this case the automatic answer does not appear in our minds, or we just simply *draw a blank*. There is some research suggesting that unconscious thinking takes place during a period when we find no fitting answer to a problem and decide to put it aside (e.g., Dijksterhuis and Nordgren, 2006; Ritter and Dijksterhuis, 2014), however, thus far no conclusive evidence has been presented that would exclude alternative explanations of incubation effects in favor of the unconscious thinking hypothesis.

When these System 1, automatic answers come to our minds, we sometimes immediately choose to take them for granted and accept them as being true without ever checking their correctness. This might be because, for example, we are pressed for time, or do not have the cognitive resources to check the answer because we are preoccupied with something else more important. It is also possible, that because these answers are pre-potent and therefore come to mind more fluently, we are more confident in their correctness (Benjamin et al., 1998). If these unchecked answers are incorrect, which they often are, in the memory literature we call them *intrusions*. Ironically, because they are unchecked, incorrect ones feel the same as if they were correct and might become one of the sources of even more blocking later on (e.g., Smith and Blankenship, 1991). An interesting question is *why* these particular incorrect answers become pre-potent in certain situations. One possibility is that

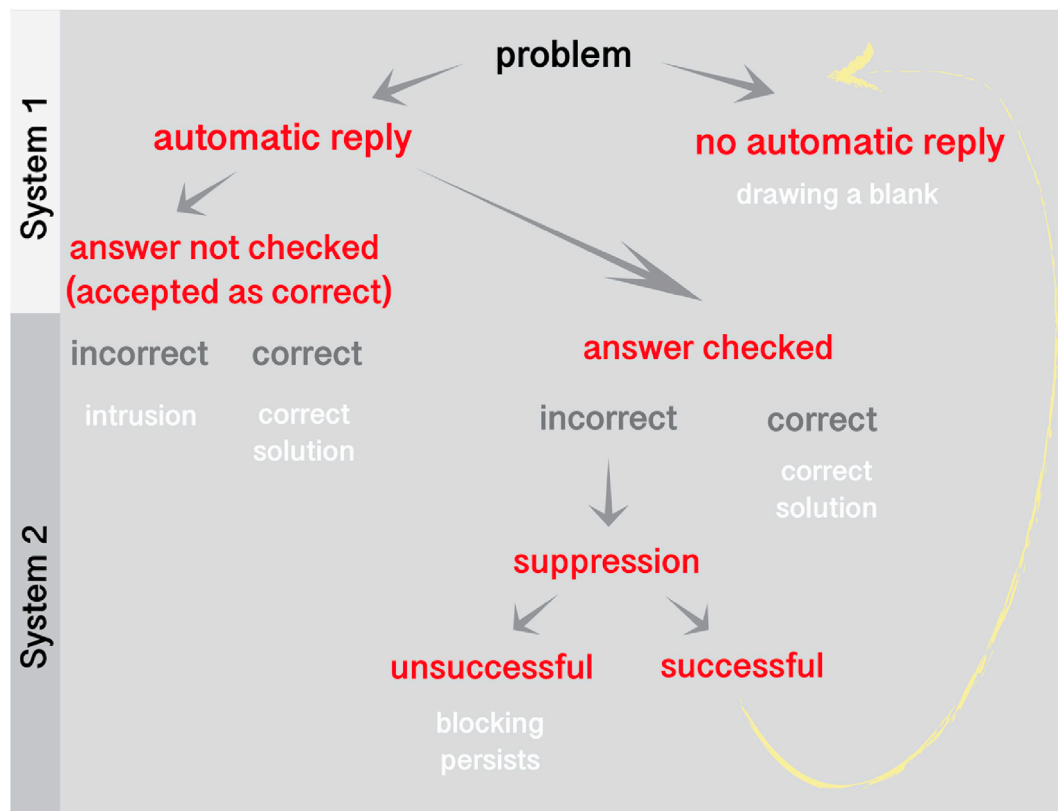


Fig. 5. Solution attempt to a creative problem.

the physical or mental environment of the problem reminds us to something we have already experienced in the past and thus poses constraints in our further attempts to solve the problem in question (Knoblich et al., 1999). This constraint limits the set of knowledge we search in our solution attempts and might lead to an impasse, if it does not contain the element necessary for the final solution. Constraints might be introduced by our own past experience as well as examples in the explanation of problems (Smith et al., 1993), or an idea from a colleague during an open brainstorming session, a phenomenon called *collaborative fixation* (Kohn and Smith, 2011).

If we choose to check whether our intuitions, or *System 1* answers are indeed correct, that already is a conscious process, part of our *reasoning* (Kahneman, 2003), or *System 2* (Stanovich and West, 2000). The brain area that has been implicated in action monitoring and error detection is the anterior cingulate cortex (ACC) (Bush et al., 2000; Devinsky et al., 1995; Kolling et al., 2016; van Veen and Carter, 2006). If these checked answers prove to be incorrect (that is, if we actually realize that our intuition is wrong) we have to keep thinking to find the correct answer. However, being already in our mind, the wrong solutions present an obstacle. We somehow have to clear our mind and suppress or replace these wrong answers to be able to carry on with our task. This process has two stages. First, incorrect items in our working memory have to be cleared to enable further thinking. Brewin discusses thought suppression of active working memory items (Brewin and Beaton, 2002; Brewin and Smart, 2005), however, the method used—having participants suppress a particular thought while providing a verbal stream of consciousness—more likely represents an interference or displacement of unwanted thoughts. This method is similar to the one described by Anderson and Hanslmayr (2014), where they asked some of their participants to try and think of something else instead of suppressing the unwanted memory items. Neural processes depend on what strategy we use to clear the working memory and what modality the intruding thought is. Interestingly enough, current evidence suggests that none of the frontal executive regions of the brain are involved differentially in the clearing of working memory. Rather, the cuneus and precuneus, implicated in attention shifts, get activated in the process (Banich et al., 2015). A secondary adaptive process, is the context dependent selective suppression of these same items we just cleared from working memory in long term memory as well, to prevent their retrieval the next time we encounter the same problem (the context dependent nature of this suppression is debated by Anderson and Green, 2001, who found this suppression effort generalizes; for evidence of cue-dependent suppression see Storm and Koppel, 2012). Successful suppression of these interlopers is difficult (as described in “the ironic processes of mental control” by Wegner, 1994), most of the time requires several trials (Anderson and Green, 2001) and the success and extent of which greatly depends on individual differences (Brewin and Beaton, 2002; Brewin and Smart, 2005). Long term memory suppression is thought to rely on down-regulation of bilateral hippocampus by the ventrolateral and dorsolateral prefrontal cortices (vlPFC and dlPFC) (Anderson et al., 2004; Anderson and Hanslmayr, 2014).

This is, however, just one side of the coin when we try to get to an answer. What good is suppressing an incorrect answer if we have no alternatives to think of? In order to find a suitable solution, we already have to possess the knowledge necessary to answer the question. Expert knowledge cannot be substituted by the ability to quickly generate ideas. If we do possess the necessary knowledge, the next question is whether we are able to build a bridge, to make the connection, to form an analogy between our currently existing knowledge and the problem we are facing. Suppression of intruding ideas is the task of cognitive control; generation of possible new ideas is the task of cognitive flexibility. Idea generation and especially the activation of links to concepts that are more remote or abstract is thought to be reliant on the already mentioned DMN (Buckner et al., 2008). So seemingly the two stages of this suppression-search process require brain areas that mostly work in a mutually exclusive manner. In fact, it has been hypothesized that the

creative process is an interaction of the frontal brain areas responsible for control and the DMN that enables lower level imaginative processes (Beatty et al., 2019, 2015). Following this search retrieved answers will, again, have to be checked for correctness.

In the light of these, what would then be the way to successfully modulate this mental process and enhance creative thinking?

2.1. How to modulate the process locally?

Modulation of automatic responses would be one of the possible approaches to enhancement of the creative problem solving process. We would need to circumvent, diminish or weaken our *System 1* automatic responses. As mentioned above, the dorsal striatum has been implicated as one of the contributors of these automatic processes; however, deep structures like the dorsal striatum cannot be directly stimulated non-invasively (although focused ultrasound in non-human primates shows promise as a tool for stimulating sub-cortex (Downs et al., 2017)). Nevertheless, there is growing evidence that targeting a cortical target of striatal innervation with non-invasive stimulation can alter activation of striatal regions and cortico-striatal connectivity (Avissar et al., 2017; Fonteneau et al., 2018; Polanía et al., 2012; van Schouwenburg et al., 2012). Thus, it might be possible to down-regulate automatic processing through cortical stimulation, however further exploration of cortico-striatal connectivity pathways would be desirable. Functional connectivity investigated using resting state fMRI and validated by diffusion MRI (structural connectivity) and PET imaging (molecular connectivity) (Skudlarski et al., 2008) could more accurately identify possible targets for stimulation. The DMN has also been implicated in at least some of automatic processes (Shamloo and Helie, 2016; Vatansever et al., 2017), but the depth of the network regions combined with the distributed nature make it a difficult target for direct modulation. So-called multifocus tDCS has been used to target multiple nodes of a network, but this work has focused on the surface motor cortex (Fischer et al., 2017). Nevertheless, tDCS to the dlPFC, part of the fronto-parietal control network that shows strong anti-correlation with the DMN has been shown to lead to alteration in DMN function. When anodal tDCS is applied to the dlPFC, activity in the fronto-parietal network is increased, while DMN activity is decreased. Reversing the stimulation, with cathodal stimulation to the dlPFC, has been shown behaviorally to increase mind-wandering (Axelrod et al., 2015), which is thought to be connected to DMN activity (Christoff et al., 2009; Smallwood et al., 2012).

Another possibility would be to help getting rid of pre-potent misleading solutions. This could be done in multiple ways. We could enhance the suppression efforts by strengthening the brain areas that are responsible for cognitive control, namely the pre-frontal areas (dlPFC and vlPFC). The unfortunate side-effect of this would be that following successful suppression, it would be harder to think of more remote alternative solutions, as this executive control enhancement would also make the constraints tighter that enable us to conduct a further memory search.

What would happen if, instead of strengthening, we tried to weaken cognitive control? It might also make our suppression efforts less effective, but in the meantime also loosen up constraints and thus possibly make way to more alternative solutions that might be able to displace the pre-potent response already in our mind. Lowering the firing threshold of the medial parietal areas with anodal tDCS might make it easier to shift attention away from misleading answers; the flip side of this would probably be how to stay on the task with more frequent attentional shifts that result. We can also facilitate parts of the DMN to try and activate more remote associations and thus invoke more distant analogies. As discussed, direct targeted modulation of the entire DMN would be fairly complicated, because it is a pretty extensive network of different nodes (Andrews-Hanna et al., 2010; Buckner et al., 2008), however, there are still some options we have, to facilitate remote associations through the DMN.

This brings us back to the already mentioned global modulation. There are several aspects of our mental state that influence the way we

think. Attentional processes, motivation, level of arousal or affective elements all moderate how effective we are in our goal-directed behavior. Furthermore, there are substances and other methods that, while influencing several different areas and/or processes in the brain, might get us in a state of mind that can facilitate the creative problem solving activity we set out to enhance.

3. Conclusions

Cognitive psychology can provide us some tools to help and enhance the output of creative ideation by fine tuning the methods of the creative process, like having an individual ideation part included in the group brainstorming session, or not including highly specific examples in the instructions of the initial description of a design project.

Cognitive neuroscience can do even more: it can selectively modulate parts of the creative process. The limitations we have right now are mostly due to our lack of knowledge about the neural correlates of the creative process and the delivery of the stimulation or suppression in humans without any kind of negative side effects. However, in the pursuit of enhancing creativity, “traditional” cognitive enhancement methods and more direct neuromodulatory methods should be used together for the desired effect (for a review of basic behavioral measures and their fit for imaging, see Benedek et al., 2019). We cannot ignore creative cognition literature when working on neural manipulation of any part of the creative process, as better understanding the mechanism of the cognitive methods would take us closer to discover how to use technology to modulate those same processes. The most influential and impactful works in cognitive neuroscience have been the ones, where the results of the behavioral part of the experiments in themselves were interesting.

Declaration of competing interest

The authors declare no competing interests in writing the article.

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