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Creative cognition: The diverse operations and the prospect of applying a cognitive neuroscience perspective

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Abstract

Creativity is defined quite simply as "the ability to create" in most lexicons, but, in reality, this is a complex and heterogeneous construct about which there is much to be discovered. The cognitive approach to investigating creativity recognizes and seeks to understand this complexity by investigating the component processes involved in creative thinking. The cognitive neuroscience approach, which has only limitedly been applied in the study of creativity, should ideally build on these ideas in uncovering the neural substrates of these processes. Following an introduction into the early experimental ideas and the cognitive approach to creativity, we discuss the theoretical background and behavioral methods for testing various processes of creative cognition, including conceptual expansion, the constraining influence of examples, creative imagery and insight. The complex relations between the underlying component processes of originality and relevance across these tasks are presented thereafter. We then outline how some of these conceptual distinctions can be evaluated by neuroscientific evidence and elaborate on the neuropsychological approach in the study of creativity. Given the current state of affairs, our recommendation is that despite methodological difficulties that are associated with investigating creativity, adopting the cognitive neuroscience perspective is a highly promising framework for validating and expanding on the critical issues that have been raised in this paper.

Keywords: Creative cognition; Conceptual expansion; Creative imagery; Constraints of examples; Insight; Alternate uses task; Cognitive neuroscience; Neuropsychology; Top-down and bottom-up processes

1. Introduction

Creativity is undeniably among the most complex of all human abilities. It is not entirely surprising then, that despite five decades of experimental investigation, there are still many open questions concerning the essential nature of creativity. What types of operations are involved when we speak of creative thinking? Are these operations interdependent? How is creativity brought about by and implemented in the brain? These are the kind of questions that are central to the cognitive neuroscience of creativity. And only when we answer such grass roots level questions can we go further to make clear claims about metaphysical questions, such as why we are such a creative species.

Our ability to broach and test primary level issues is entirely constrained by the methods we have at hand for use and there are many limitations with regard to the kind of neuroscientific paradigms that can be adopted in creative cognition research. We commence this review with an introduction to the theories relevant to the cognitive approach for creativity. This is necessary not only in order to clarify our current knowledge regarding the intricate nature of creative cognition, but also to be able to prioritize which questions need to be tackled first, and to determine which methods would be most appropriate for this purpose.

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1.1. Early ideas and definitions

Using the psychometric approach, J. P. Guilford [1–4] was the first researcher who both systematically theorized about and experimentally investigated creativity. Creative or "divergent thinking" was held to be principally synonymous with the level of fluency, flexibility and novelty of generated ideas, followed by the elaboration and redefinition of ideas secondarily. Divergent thinking refers to unbound ideational searching or open-ended thinking that is typically evoked in creativity tasks where solutions need to be generated for problem situations that do not have any right or wrong answers. Using such ideas as a foundation and by elaborating on one or more of these predefined variables, a number of tasks and test batteries were devised to gauge and quantify creative ability or divergent thinking [4–6].

1.2. The cognitive approach

How differences at the level of information processing operations can influence creative ability is at the heart of the cognitive approach to creativity. The most influential early model within the cognitive domain is that of Mednick [7]. Within a semantic network, concepts are associated with differing strengths to one another. The level to which a certain concept activates another concept reflects the remoteness of the two conceptual representations. The word "table", for example, tends to more strongly activate the concept "chair" compared to the alternative concept "multiplication". The level of associative strength between concepts varies widely from individual to individual. A less creative person is believed to be characterized by steep associative hierarchies in semantic networks, such that a stimulus activates many closely associated or stereotypical representations and few remotely associated or unique representations. Highly creative persons, in contrast, have flat associative hierarchies, such that they have comparable access to both closely and remotely associated concepts. Mednick's ideas therefore essentially suggest that our ability to be creative is limited by the manner in which our semantic networks are organized.

Mendelsohn [8] argued from an alternative perspective that pertained to the type of access one has to conceptual representations, which is determined by how attention is focused. In doing so, he highlighted the role of "defocused" attention or a widened attentional capacity in the ability to be creative. The principle of this argument is that to arrive at a creative idea, conceptual elements that are within the focus of attention need to be combined. The more the number of elements present within one's attentional stream, the greater the number of possible resulting combinations. For instance, if one is able to only attend to two conceptual elements at the same time, only one combination would arise. If, however, one is able to attend to four elements at the same time, six permutations would be possible. So this theoretical view stressed the importance of the manner in which information from conceptual networks can be accessed, which has an effect on the amount of information available within the attentional stream. It also broached the issue of the free manipulation of representations within the attentional focus.

The two models share some common ideas about the kind of information processing biases that could influence creative expression. Both conceptualize creative thinking as the ability to activate remotely represented ideas and concepts, although this activation process is described with reference to the type of attentional control wielded during semantic retrieval in Mendelsohn's model, whereas Mednick's model refers to the structural organization of long-term semantic memory networks. However, as most creativity tasks have not been designed to tease apart such closely coupled processes and states, what one can conclude about the precise dynamics of the underlying cognitive operations when carrying out such tasks is limited.

In the 1990s, a group of cognitive scientists introduced finer and more rudimentary distinctions when they sought to specify different kinds of mental operations that underlie creative thinking within their Geneplore model of creative cognition [9,10]. This approach to investigate creativity, unlike that of Mendelsohn and Mednick, was not focused on individual differences in creative ability, but was instead directed solely at examining the mental operations involved in creativity. The various processes underlying creative thinking were held to have two components in common, which were in many ways similar to those proposed by Guilford [3]. All involve the initial generation of potential ideas or "preinventive" structures, such as the formation of associations between stored conceptual structures in memory and the analogical transfer of information from one domain to another. This phase is followed by extensive exploration and interpretation of these ideas by, for instance, searching for the desired attributes or conceptual limitations of the generated structures and the evaluation of structures from different perspectives. The focus of the creative cognition approach was thus very different from information processing bias accounts of that of Mendelsohn and Mednick. For the latter, the focus was that of outlining the type of cognitive style that typifies highly creative populations, whereas in creative cognition, the micro level is to characterize the creative processes themselves, which would be the same for everyone.

In emphasizing that several types of cognitive operations are involved in creative thinking, which can be assessed by examining normative cognitive processes under explicitly generative conditions, this was the first approach to truly acknowledge the multifaceted nature of creativity. A number of such cognitive processes have been identified for which several tasks have been developed and some of them will be expanded on in the next section.

2. Creative cognition: concepts and methods of assessment

The concepts and tasks introduced below that stemmed from the Geneplore model are conceptual expansion, constraints of examples and creative imagery. Apart from these, the alternate uses task and methods to investigate insight are also described.

2.1. Conceptual expansion

A concept is a notion or idea (often implicit) about features or parameters that define which objects or events belong to the same class. One does not have to know all the chairs in the world, for instance, to have a usable concept of a chair that can be modified with learning. Conceptual expansion, as the term suggests, refers to the ability to expand concepts [11]. What is assessed in a conceptual expansion task is the extent to which one can widen the parameters of a concept or broaden a concept's existing structure or usual definition. In the original task that was devised to assess conceptual expansion, subjects were asked to imagine and draw an animal that lives on another planet, which is very different from Earth. What is assessed is how far the person's drawing of an animal deviates from ordinary schemas of animals on Earth in general, i.e., of having certain fundamental features like bilateral symmetry of form, presence of common appendages (like legs and wings), presence of common sense organs (like eyes and ears), and so on. The usual pattern found in these drawings is that ordinary concepts of animals, in terms of their essential features, actively guide and pose considerable limitations on an individual's ability to create a new type of animal. This tendency to draw on generic exemplars of animals, even when explicitly instructed not to do so, is what is termed the path-of-least-resistance approach, which is the most commonly employed strategy when faced with this kind of generative task [11–14].

2.1.1. Assessing conceptual expansion with the animal task

In our own studies [15–18], we allowed subjects a maximum of 5 minutes to imagine and think about an alien animal after which they were required to draw the animal on a sheet of paper using a pencil. This is a very generous time limit and most subjects require far less time to begin putting their ideas down on paper. The subject's drawings were coded in accordance with the procedures described by Ward [11,15] with the help of two independent scorers, who had to note the presence or absence of the following features: bilateral symmetry of form, appendages (legs, arms, wings, and tail), sense organs (eyes, mouth, nose, and ears), atypical appendages, and atypical sense organs. A coding was deemed valid when both scorers were in agreement. In the occasional situation when both scorers were not in agreement, which usually occurred in less than 2% of all observations, a third scorer was consulted and the majority result accepted.

The coded data was then used to yield the five sub-elements of conceptual expansion: (a) bilateral asymmetry, (b) lack of appendages, (c) lack of sense organs, (d) unusual appendages, and (e) unusual sense organs. In the case of elements (b) and (c), when one or more of the four customary appendages or sense organs were present in a drawing, it would qualify as a presence of an appendage or sense organ. Only a complete absence of all customary appendages and sense organs would be scored as lack of appendages or a lack of sense organs. The presence or absence of an element gave rise to a score of 1 or 0. The total expansion score for a drawing thus ranged from 0–5.

Therefore, the better one can imagine an animal that does not have a bilaterally symmetrical form, that lacks the customary appendages and sense organs found on most Earth animals and, furthermore, has unusual features that are not found on most animals on Earth (like wheels instead of feet), the greater one's conceptual expansion. Examples of high and low degrees of conceptual expansion are given in Fig. 1. Tasks have also been devised to test conceptual expansion in other conceptual domains, such as imaginary fruits, tools, and faces [14,19].

2.1.2. Guidelines for employing the conceptual expansion animal task

What is critical for the proper assessment and coding of the drawings is that all the necessary information is present. It is essential, for instance, that the participants draw the animal from two perspectives (front and side). Only then can the appraisal of bilateral asymmetry be made. One recommended strategy is to make a priori decisions about what kind of drawings will not be taken into consideration. For instance, some subjects evade actually performing the task by drawing a simple object like a point or a circle. These cases can be quite easily identified, as the subjects typically have little or no explanation for the type of animal that the drawing reflects. To control for such occurrences, it would be helpful to have some standardized assessment of the subject's motivation to perform the task taken in the form of a self-rating ("How much did you like the task?") or as an indirect behavioral measure ("Would you like to do another one?"). Otherwise there is the danger that an unmotivated subject, who simply does not try to think of an animal during performance of the task, obtains an unfair medium score (e.g., 2 points for lack of appendages and lack of sense organs) without having tried to produce anything creative.

To understand the function of a particular appendage or sense organ, one should prod the subject for details. All information should be written down or recorded as the subject provides it and given in its full form to the scorers. This is done so that the scorers are easily able to understand the drawings and to ensure that the experimenter does not influence what kind of information is passed through to the scorers. However, it is critical that the drawings are assessed on the basis of what is drawn and not the explanations. Very often, subjects have wonderful ideas about different worlds and what the animal they produced can do in that world, but the drawing itself is a very typical animal drawing akin to a cow or a cat. Unless one comes up with a priori criteria from which to assess such ideas about what the generated animals are capable of, as distinct from the con-

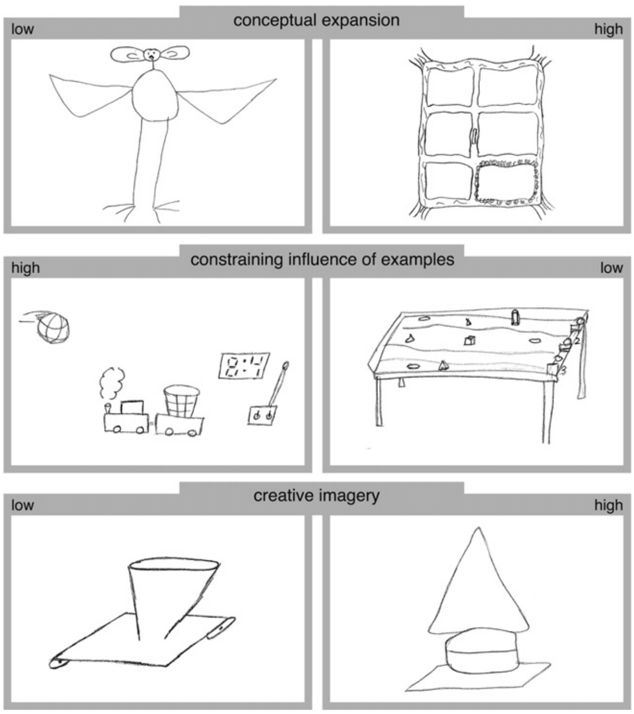

Fig. 1. The examples in the top panel are from the conceptual expansion task. The animal on the left illustrates low conceptual expansion, as the customary appendages and sense organs are present, no unusual appendages or sense organs are featured, and the creature is bilaterally symmetrical. The animal on the right, in contrast, reflects high conceptual expansion on all counts. The middle panel shows instances from the constraints of examples task. The toy on the left is severely constrained by the previously presented salient examples as the toy contains the presence of a ball, electronics and much physical activity. The toy on the right, though, involves a game in which little paper pyramids that float on water have to be pushed to the end by blowing through the holes on the side of the board, while avoiding the obstacles in the way. This toy is comparatively far less constrained than the one on the left. The bottom panel shows instances from a trial in the creative imagery task where the category was "tools and utensils" and the figures to be manipulated were a cone, a flat square and two wheels. The invention on the left represents a bowl that can be rolled across a surface. It scores low on practicality, primarily because the bowl itself is not stable in structure and is hence not very functional. It also scores low on originality because a bowl was not judged to be an unusual utensil. The invention on the right, on the other hand, is supposed to represent a device that can be used in the garden to bore a hole into the soil. The hole can be bored using the pointed part of the cone, while the flat square serves as a handle to hold when pushing the device. It also serves as a base when the device is stored away after use. The tires are grouped together to form a support in between the cone and the flat square. It serves as a marker indicating that the hole is deep enough once the cone is under the soil, and provides the space between the other two parts to aid the removal of the device from the soil. Compared to the invention on the left, this one scores higher on both practicality and originality.

ceptual expansion of drawings itself, this information should not unduly sway the scorer when assessing the drawings.

2.2. Constraining influence of examples

Functional fixedness is a type of cognitive bias that poses limits on the ability to conceive of an object in a manner that is different from what it is customarily known to be. This concept was first explored by the Gestalt psychologists within the purview of insight in problem solving [20], which is a process that will be explored in a later section. There have been many investigations concerning which kinds of situations can induce such fixedness biases. Luchins [21], for instance, has showed that a mental set or Einstellung can be imposed by the repeated use of a particular strategy during mathematical problem solving. While this kind of mental set can be circumvented easily with a prior warning to the subject, other processes by which mental sets are brought about are less resistant to change. One such phenomenon is the effect of examples in the generation of new ideas.

When subjects are asked to generate novel ideas for toys or animals after being exposed to exemplars of novel toys or animals by the experimenter, the ideas they produce tend to conform to the ideas in the examples [22,23]. This conformity is induced by exposing the subject to the same fundamental features across all the exemplars. The degree to which the ideas generated by the subjects incorporate these features from the exemplars is an indication of constraining effect of recently activated knowledge, in the form of pertinent examples, in generating new ideas.

2.2.1. Assessing the constraining effect of examples with the toy task

In this task [15,16,18,23], subjects are asked to imagine that they were employed by a toy company that is in need of new ideas for toys. The subject's task was to imagine and draw a new and different toy of his or her own creative design. Duplication of toys that currently exist or previously existed is not allowed. Prior to the drawing of the toys, the subject is exposed to exemplars of three examples of toys taken from Smith, Ward, and Schumacher [23] that have three fundamental elements in common: the presence of a ball, the presence of intense physical activity and the presence of electronics. The subjects are given 5 minutes to think about what they would like to draw and their drawings are assessed on the extent to which they include these three fundamental features of the examples. Two independent scorers note whether the subjects' drawings contained any of these three elements. There is usually complete agreement between scorers on all counts. If the situation arises when this is not so, a third scorer should be consulted. The total score on this task ranges from 0 (none of the three common elements of the toy examples were present in the subject's drawing) to 3 (all three elements of the toy examples were present). Therefore, the higher the score, the stronger the constraining effect of the examples on idea generation. Fig. 1 shows one instance of the highly constraining effects of examples alongside another instance in which this constraining effect is overcome.

2.2.2. Guidelines for employing the constraining examples toy task

This is a relatively simple task to administer and to assess so the potential for problems is low. What is important is that the examples are presented immediately after the instructions are given about what is required of the subject. This is so that the possibility of actively thinking about what kind of toy they can draw before seeing the examples is circumvented. It is also essential that the participants are properly informed about how the example toys function so as to be sure that the constraining effects are brought about.

In addition, just as in the case of the conceptual expansion task, all information provided about each toy should be recorded as the subject provides it and given in its full form to the scorers so that they are easily able to understand the drawings.

2.3. Creative imagery

Based on historical and anecdotal accounts of the significant role of mental imagery in aiding insights, discoveries and artistic expression, creative imagery refers to the vividness of abstract imagination during the generation of a product. The creative imagery task [24] explores how creativity can be fostered in generating innovative inventions under laboratory conditions. In this task, the aim is to construct an object that falls into a given category (e.g., transportation) using three randomly assigned simple 3-dimensional figures (e.g., a sphere, a cone, and a cross). The invented object is then judged on two measures—originality, or how unusual the object is, and practicality, or how functional the object is.

Although the task allows much flexibility in combining and blending the elements to produce an object, it necessitates high levels of abstraction and mental imagery as it does not relate directly to or tangibly draw from other kinds of familiar processes. When this task is made easier by having the subjects freely choose the figures or the categories in a trial, the resulting inventions are generally far less original than when the choice of elements is randomly determined by the experimenter [24]. This is because subjects generally look for the easiest way out (for e.g., picking out a sphere as a figure when faced with the category "transportation" so that a wheel can be easily made) and tend to pick the figures that easily fit with their readily available ideas of typical objects in a category. This implies that the inventions are judged to be more creative when a path-of-least-resistance strategy is prevented, just as in the conceptual expansion task.

2.3.1. Assessing the creative imagery task

The objective of the participants in this task is to assemble an object that falls into a predetermined category using three figures from an array of simple 3-dimensional figures (for a list, see [15,16,24]). Except for altering the form of the figures, the participants are allowed to vary the figures provided to them in any way with regard to size, orientation, position, texture, and so on. The participants are required to use all three figures and are supposed to put them together in a meaningful way so as to form a useful object from a certain category. They are given 3 minutes per trial to imagine an object and each trial consists of a unique category-figures combination.

The inventions are subsequently rated by two trained raters along the dimensions of originality and practicality using a five-point scale, and the average of their ratings is taken as the final score for the inventions. Each participant consequently obtains an average score of originality and practicality from the inventions they generated across trials. Examples of relatively low originality/low practicality inventions compared to relatively high originality/high practicality inventions are given in Fig. 1.

2.3.2. Guidelines for employing the creative imagery task

In the original version of the task, the figures and categories for every trial were randomly assigned to the subject. Although we adopted this approach in our earliest studies [15,16], we employed another version of the task in more recent studies [17,18], where every subject was presented with the same combination of figures and categories on all trials. We found the latter approach more advantageous on many counts. The drawings using the second approach were easier for the raters to judge as they could compare the drawings of all subjects for each trial and get a good feeling for what was the norm. This, in turn, resulted in higher inter-rater reliabilities by reducing random error variation in the data.

As this is the most subjective task of all, it is also the most problematic in terms of scoring. It is important that the raters are very clear about what they have to do and are given enough training (for more details, see [24]). What is crucial is that they learn how to separate the concept of originality or uniqueness from that of practicality or usefulness. Examples of inventions of all four extreme groups—high originality/high practicality, high originality/low practicality, low originality/high practicality and low originality/low practicality—would be a vital aid.

2.4. Alternate uses task

One of the most widely employed tasks in the assessment of divergent thinking over the decades has been the alternate uses task, which was introduced by Wallach and Kogan [6] in their investigations of creative potential in children. Although this is not one of the tasks devised within the Geneplore model, its simplicity and extensive use in experimental studies warrants that it is also discussed in relation to the other tasks. The dependent measures of the alternate uses task are "fluency" and "uniqueness", which are regarded as two discrete aspects of divergent thinking.

2.4.1. Assessing the alternate uses task

The task required of the participants here is to generate as many uses as possible for common objects, such as a newspaper, a brick or a shoe. In our experiments with this task, subjects are allowed 2 minutes per object for generating uses. The flexibility of the participant's thought processes in this generative situation is assessed on the basis of the fluency and the uniqueness of the responses. Fluency is judged by the number of discrete solutions generated for each object and uniqueness is assessed by the infrequency or originality of the generated use. To take the example of a shoe, using it to stamp an insect is considered to be a less original or unique idea as compared to using a shoe as a flowerpot.

2.4.2. Guidelines for employing the alternate uses task

What typically varies from study to study is the number of objects used when assessing uniqueness and fluency as there is no thumb rule. Given that an increasing number of trials generally boost the power of an experimental design, the more objects for which alternate uses have to be generated, the better. Perhaps a more critical point is how fluency and originality are assessed. Fluency is more easily assessed, as one has to only keep track of how many uses are generated. However, it is important to differentiate between discrete uses and to alert the subject to the fact that different uses are being asked for. To use a brick in constructing part of a wall of a house is similar to using a brick to build a barbeque. In both situations, a brick is used as building material. This point is particularly important to keep in mind when investigating clinical populations on such tasks because, very often, they show perseverative responses. Clear instructions and reminders of the task goals are thus necessary.

Quite another matter is the assessment of originality. We employ the original assessment protocol in scoring a response as being unique only if one person in the whole sample has generated such a response for that trial [17]. A person's total uniqueness score is then the sum of all unique responses made across all trials. The alternative method of assessment is the more common one of having two or more raters judge a response based on its originality or unusualness. Both procedures have its advantages and disadvantages. The former approach is objective and strict, but it provides only a relative measure (depending on the sample size and sample characteristics) and is focused only on extremely unique responses. In comparison, the latter approach is more subjective, but it allows for the assessment of intermediate values that can be compared across different samples and studies.

2.5. Insight

One method of classifying analytical problems is by distinguishing between insight and non-insight or incremental problem solving [25–29]. Both problems types have well-defined means, or conditions of the task at hand, and a specified goal, which is the solution that is to be reached. What makes problem solving strategies 'incremental' in an analytical task is that the goal is attained in a stepwise manner and generally follows an incremental pattern [30,31]. Solving an insight problem, in contrast, requires restructuring or a vital change in the representation of the elements of the problem [20,32]. The progression during the problem solving process is, therefore, not incremental, but involves a sudden discovery of a solution, a phenomenon that is also commonly referred to as the "aha" experience. The Tower of Hanoi is an example of an incremental analytical problem, whereas the Duncker Candle task [20] is a classic insight analytical problem.

Evidence in favor of the involvement of different cognitive operations while solving insight and incremental problems primarily stems from two sources. First, subjective predictors of performance in problem solving, like feelings of approaching the solution during the solving process, were relatively accurate in the case of non-insight and incremental problems, but not for insight problems [25,26,31]. Second, verbalization of strategies adopted during the problem solving process was found to thwart the solving of insight problems, but had no effect on the solving of incremental problems [28,33]. As logical problem solving strategies are utilized during incremental problem solving, the verbalization of these stepwise strategies would not interfere with the solving process itself. However, metacognitive processes are involved in insight and having to verbalize these essentially un-reportable processes disrupts the solving process.

It is important to note that all forms of problem solving tasks require convergent thinking. This is because the tasks are designed such that a single, definitely correct solution for the problem exists to which the activated cognitive processes converge. In contrast, most creativity tasks require divergent thinking in the sense that a potentially indefinite number of solutions are possible (cf. the alternate uses task). The process of insight problem solving is an interesting mixture between these two thinking modes, convergent and divergent. It is convergent in the sense that it aims at a single correct solution. However, it also requires divergent thinking, as the problem needs to be restructured by means of flexible thought, i.e., "functional fixedness" needs to be overcome [34].

2.5.1. Assessing insight problems

There is abundant literature on insight problem solving [35], and for a list of analytical problems, the database provided by Weisberg [29] is a comprehensive one. In our own studies [34], we have contrasted performance on insight problems relative to incremental problems that are comparable in terms of the kind of domain involved, such as mathematical problems or riddles. Within the paradigms we use [34], subjects are allowed a maximum of 4 minutes for the solving of each problem. If a subject gives a wrong solution to a problem within this period, they were given an explanation about why the solution was wrong and were allowed to continue working on the problem until the 4-minute period had elapsed. Each problem is scored with either a 1 for the successful solving of a problem or a 0 when the problem is unsolved. The total score on insight or incremental problem solving is a sum of all the correct responses for each problem type.

2.5.2. Guidelines for employing insight problems

Due to the fact that there are many types of insight problems, there is a lot of choice in the kind of task that can be employed. But this very fact is the cause of the disadvantages one faces when using analytical problems to test insight. What is essential is coming up with good criteria for including certain tasks and not others, such as the level of difficulty. This usually needs to be determined on the basis of pilot studies on large enough samples. Another factor is how much time one has to carry out an experimental session, as this poses severe limits on how many problems can be used. There are also no guidelines by which one can determine how many problems constitute a minimum requirement for a study because this varies depending on what exactly the study aims to convey. In general, the larger the number of problems that are employed, the stronger the conclusions that can be derived.

The downside of using analytical problems to test insight has been very well outlined in a recent review [36]. This paper advocates using a variation of the remote associates task to test insight as well as asking subjects after they solve each trial if they had an insight experience or not [37]. In the remote associates task, subjects are presented three words (e.g., boot, summer, and ground) for which they have to find a common connecting concept (e.g., camp). Attaining the solution to such tasks usually requires insight. The advantage with such an insight task is that one overcomes the problem of having too few trials and task difficulty can be better controlled. The advantage in using analytical problems is that because one assesses insight at an undoubtedly more complex plane, the information processing involved in such scenarios is perhaps closer to that of everyday life situations.

2.6. Concluding notes regarding creative cognition

The study of creative ability from different psychological domains has led to numerous conceptions of what creativity entails and how it can be assessed. The presence of originality is considered to be the defining factor that is crucial to the assessment of how creative a product is. A response is usually judged to be creative to the extent that it is novel, unique or unusual. This is evident not only from the early theoretical conceptions of Guilford [1–4], Mednick [7], and Mendelsohn [8], but also from the later models that specify the component processes underlying creativity, as assessed by experimental procedures such as the conceptual expansion task, the constraints of examples task and the creative imagery task [9,10]. The second factor which is also often considered to be critical in most approaches to creativity is that of relevance or how useful or appropriate a response is to achieving a particular end [38].

Although this distinction seems clear enough, creativity tasks vary considerably with regard to the interplay between these two factors (as well as in the extent to which they are related to one another and certain personality constructs. For details, see [15–17]). Within the creative imagery task, the scoring is such that these two components of creativity can be separated assessed. This is not so for the other tasks reviewed earlier. In the conceptual expansion task, for instance, the relationship between originality and relevance is an inverse one. The fewer the number of relevant animal features in the generated novel animal, the greater the conceptual expansion. Performance on this particular task would thus profit from the ability to disregard relevant conceptions of biological structure and function.

A somewhat similar situation also appears to be involved during insight in problem solving, as it requires a mixture of divergent thinking (to mentally restructure the problem and discover alternative strategies) and convergent thinking (to relate and direct these unusual ideas to a useful solution of the problem). The response space for the extent of divergent thought is, of course, more limited here than in the open-ended tasks. In insight problem solving, the (overtly) most relevant course of action is the incorrect one. Only overcoming this task set, by focusing on less relevant and more unusual strategies, would help solve the problem.

The alternate uses and the constraints of examples tasks can also be understood within this context. They are similar in that the responses of these tasks must fit a certain context—that of an object of amusement in the constraints of examples task, or a material dependent use in the alternate uses task. While both assess originality, they induce demands on relevance at different levels. In the constraints of examples task, the concept of relevance is limited only to the currently pertinent examples in that the originality of one's own responses is contingent on the extent to which one avoids incorporating relevant features from the examples. For the alternate uses task, on the other hand, wider constraints affect the relevance of the invented use, which include not only the prepotent use for a material, but also the properties of the material itself, such as its weight, shape, size, flexibility, and so on.

Insight problem solving and the constraints of examples tasks are similar in that an immediate, salient and circumscribed context of what is relevant must be overcome to perform well. In the conceptual expansion and alternate uses tasks, on the other hand, the relevant context that poses restrictions on the ability to be original is broader and less immediate, as it is conceptually bound to a wider semantic category in long-term memory. It, therefore, seems that the dimensions of originality and relevance are, to varying degrees, in conflict with one another. Too much emphasis on relevance tends to have a detrimental effect on originality, and vice versa, which is similar to what H. J. Eysenck has maintained in his work on personality and creativity [39]. However, claims concerning the extent of this negative association are limited. It depends not only on which creative cognitive process is being targeted, but also in terms of how relevance is conceived [17]. This complex relationship between originality and relevance is a critical one when speaking of creativity, and one that needs to be given due attention.

3. Adopting a cognitive neuroscience approach in the study of creative cognition

Cognitive neuroscience involves relating cognitive functions to their underlying brain basis. We can link the relevance dimension in creativity to findings on goal-related thinking, planning and task monitoring [17], which depends crucially on the prefrontal cortex [40,41], or, more specifically, on the flexible top-down control this structure exerts over the activation patterns in more posterior systems that represent pre-established sensory, memory, and motor processes [41–43]. Thus, the extent to which creative processes require evaluating the relevance of ideas, maintaining prespecified goals and pursuing those goals will be reflected by the recruitment of those functions of the prefrontal cortex [44–46]. In contrast, almost by definition, the free associative processes involved in originality involve a broadening or "deployment" of attention [47], which necessarily conflicts with the highly focused and goal-directed processes mediated by the prefrontal cortex. A possible trade-off between the originality and the relevance components should therefore be taken into account in theoretical and empirical work in creativity.

However, this idea cannot explain all facets of creative cognition because how factors affecting relevance interact with those that affect originality differ a great deal depending on the contextual demands of the task [17]. The very concept of top-down processing has many different meanings [43,48,49], only some of which relate to prefrontal cortex function. In our own work, we have distinguished between active and passive forms of top-down concept activation in purely divergent thinking [16–18], where "active" refers to conditionally salient representations in working memory, and "passive" refers to implicitly activated generic representations from long-term memory. An example of the activation of an active context would be in the constraints of examples toy task, where novel and salient object features that are pointed out explicitly to the subject, need to be inhibited. The conceptual expansion animal task provides a set-up for passive contextual activation, where a concept is invoked but not manipulatively elaborated upon.

It is important to note, however, that the prefrontal cortex is engaged not only in directing and maintaining focal attention onto a certain goal, but also in the voluntary suppression of previously maintained representations that are no longer needed, as well as in the flexible shift between different goals and mental sets [41,43,49,50]. These processes also seem to be important factors that underlie the ability to generate original or unusual responses.

Other concepts of information processing may also need to be taken into consideration when considering originality. Generating an original response generally requires the activation of distant and relatively loosely connected representations, which are stored in more posterior cerebral networks. The uniqueness of generated responses could therefore depend on how semantic networks are organized in the temporal lobe. Alternatively, response uniqueness could also be a function of the manner in which semantic selection, i.e., the selection of relevant information from competing conceptual representations, is exerted. The left inferior frontal gyrus is considered to play a key role in the process of semantic selection [51,52]. The originality and relevance dimensions are thus likely to depend on different aspects of brain function, with the latter being linked mainly to top-down facets of information processing, whereas the former is likely to derive from a more complex interplay between top-down and bottom-up processes.

It should also be noted that automatic unconscious processes have also been implicated in the production of unusual responses, particularly in studies that involve a period of "incubation," where the goal-related focused search for a solution was replaced temporarily by a period of unrelated demanding cognitive activity [53] or even sleep [54]. How exactly this happens is still an open question.

So, the concept of originality in itself and how it correlates with the dimension of relevance, depending on the process under study, is a crucial one to get to grips with if we are to understand creativity and its relation to different facets of cerebral function. Although the PFC seems to play a critical role in the ability to be creative, it cannot be claimed that this is the sole structure that is implicated in such complex cognition. Just as in other fields, such as theory-of-mind, where a network of neural areas has been identified in underlying complex social cognition [55], a network perspective also needs to be adopted when conceiving of creativity. These issues need to be kept in mind when employing any experimental paradigm.

From a methodological standpoint, it is a challenging enterprise to verify the theoretical ideas advanced here and elsewhere [45,46,56] about the neural foundations of creativity using the complex and highly restrictive experimental techniques commonly used in cognitive neuroscience. This is because of the very nature of creativity tasks. Compared to classic objective behavioral measures like reaction time, creativity measures are not only problematic because they are usually subjective. What is more critical is the kind of response that is usually required in creativity tasks, as it very rarely involves a simple button press response. Instead, more elaborate responses of vocal or written expression are needed, which means that each trial is time consuming and involves a great deal of movement. Both these factors are obstacles in the attempt to relate the cognitive component processes underlying creativity to their neural substrates. The use of neuroimaging and electrophysiological techniques in creativity research are covered in detail elsewhere in this special issue. We provide a brief review of existing neuropsychological evidence in relation to creativity.

3.1. Neuropsychological approaches

Creativity research has only been limitedly carried out from a neuropsychological perspective on neurological populations. This is odd when considering that neurologically based studies have always provided a sort of litmus test for theories about cognitive function in healthy individuals. Early conceptions about brain function in creativity claimed a key role for hemispheric dominance based on studies of patients with corpus callosotomies for epilepsy [57,58]. Reduced left hemisphere dominance was held to be related to wider associational thinking and, consequently, enhanced creative ability. This idea has been corroborated on healthy populations using fMRI [59] and laterality studies [60].

Some researchers have taken this a step further by directly studying circumscribed lesions in the brain and the manner in which they affect creative output. Bruce Miller and his colleagues [61–63] found that in a minority of patients with fronto-temporal dementia (FTD), remarkable artistic abilities developed post-stroke in individuals even with no prior training or background knowledge in art. Such abilities were mainly found in patients with the temporal lobe variant of FTD, i.e., where the dorsolateral prefrontal cortex is spared. This result implies that it was not the conceptual selection as much as the manner in which the semantic networks are organized in the temporal lobes after damage that would account for the difference here.

On the other hand, a recent experimental study has shown that patients with lesions of the dorsolateral prefrontal cortex performed better than healthy control participants when solving abstract insight problem solving tasks [64]. Given that this prefrontal region has been hypothesized to be involved in defining a set of responses that are suited for a particular task, which are then biased to be selected [65], Reverberi et al. [64] attributed this advantage on the part of the neurological patients as being due to a less biased response space. This result is a nice demonstration of the idea that strong top-down control can have detrimental effects on divergent aspects of information processing during convergent thinking.

The results on the frontal lobe patients are seemingly in conflict with the observed findings of higher artistic creativity in FTD. This implies that apart from having to conceive of the facilitative versus detrimental effects of different aspects of prefrontal function, we may additionally need to differentiate between domain-specific aspects in creativity, that underlie artistic creativity or mathematical genius, from domain-general processes in everyday creativity, that can be tapped using the tasks introduced earlier. The role of the prefrontal cortex is presumably restricted to domain-general creative processes, whereas other cerebral areas are more likely to be implicated when it comes to domain-specific facets that are affected by the architectonics or the type of connectivity within neural networks. Dietrich [45] has argued along similar lines in proposing a distinction between creative insights that are arrived at after concerted deliberation, which are PFC-driven, from those that are arrived at spontaneously, which are driven by the more posterior regions in the brain. This would also relate in part to the distinction between the ideas of Mendelsohn and Mednick, where the uniqueness of a response was said to depend on either the type of access to conceptual representations [8] or the very manner in which semantic networks are organized [7].

What all of this ultimately really exemplifies is that the simple search for "brain regions involved in creativity" is both fruitless and uninformative unless a more thorough approach is adopted. The very first step would be to define at the outset what makes a product creative at all. Is, for instance, being able to draw an animal with more elaborate features [66] a sign of creativity or simply a matter of enhanced sketching skills and a better eye for detail? And if the latter is the case, how is it related, if at all, to producing an original response? Depending on how such questions are answered, the interpretations of the functions of brain regions that are purportedly involved are overwhelmingly variable. It is therefore crucial that such questions be posed because clubbing everything that seems intuitively creative into one common scheme to understand creativity is a recipe for disaster.

The best way forward would be to begin by breaking down the underlying cognitive processes involved in tasks that are aimed at tapping creative thinking into subcomponents. The involvement of different regions of the brain in each of these processes, whether overlapping or discrete, can be determined by, for instance, employing a comprehensive neuropsychological approach testing diverse neurological populations. This would aid not only our understanding of how different processes that are involved in creative thinking interact and how they differentially relate to brain function, it would also allow us to devise appropriate paradigms to test more circumscribed processes using neuroimaging and electrophysiological techniques. Given the current state of how much is unknown about the relation between creative cognition and brain function, we propose that adopting such a neuropsychological approach would provide most constructive first means by which we can vitally advance our knowledge.

4. Concluding remarks

Creativity is undoubtedly an incredibly complex construct. The cognitive approach to studying creativity has been revelatory of the amazing variety of mental operations involved in creative thinking. In many ways, it seems that the time has now come to start from scratch in thinking about how to study creativity if the goal is to relate it to brain function. Carrying out investigations on one facet of creative thinking and generalizing it as explaining all of creativity is definitely a strategy that can no longer do. The way forward would be to take a process-based approach, such as that of the Geneplore model of creative cognition, by defining a process which reflects one facet of creative thinking, and to then use the appropriate tools to assess the features of this process in cognitive and neural terms.

Our proposal to distinguish between the contributions of prefrontal cortex based processes aiming for relevance with regard to how this structure, in concert with other brain areas, differentially affects the generation of original and unusual connections is only a very basic and preliminary attempt into the proposed direction, and certainly not the only one [45,46,56]. These ideas need to be elaborated further theoretically and empirically to become a fruitful framework. To verify the proposed ideas and analyze their implications, a neuropsychological approach would be the most promising first approach to adopt, preferably in conjunction with cognitive neuroscience methods that could provide a modular index not only of the brain regions activated during task performance, but also of the functional cooperation between the involved regions and the temporal dynamics of the processes.

Neuroimaging and electrophysiological studies on non-clinical populations could be used to validate and vitally expand on the insights gained from such approaches by using tasks that are tailored to tap circumscribed processes. The last frontier would be to go beyond the current strategy to map creative sub-functions onto macroscopic brain structures and to develop a computational understanding of the neural system dynamics underlying the various kinds of processes involved in creative thinking. To get to this stage though, we first need to attain a coherent and comprehensive understanding of the mental operations underlying creativity and its neural underpinnings. This, in turn, is only possible if we begin by attempting to unravel the fascinating complexity that is central to the very construct of creativity, and the creative cognition approach provides an ideal launching pad for such an endeavor.

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