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Four Mental Operations in Creative Cognition: The Importance of Abstraction

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ABSTRACT: In reviewing existing theories of creativity, 4 mental operations seem to account for creative cognition: application, analogy, combination, and abstraction. The defining characteristics and the resulting products of these 4 operations are discussed and broad implications for understanding cultural movements, such as surrealism and renaissance, and scientific revolutions, such relativity theory, are explored. These operations form an ordinal scale of innovation, but are not predictive of the impact or success of the creative product. The abstraction operation is stressed, having been relatively neglected in the literature on creative cognition. Careful distinction between these 4 operations may shed new light on the sudden-gradual and special–ordinary controversies that exist in the field. Further, the often-used insight problem methodology is insufficient for studying the full range of creative operations. Examples of a more adequate methodology are provided.

Creativity has been the object of formal academic study for over a century and of philosophical reflection for more than 2 millennia. In spite of ingenious experimental design stemming from traditions such as Gestalt (e.g., Kohler, 1925; Wertheimer, 1945), Associative theory (e.g., Mednick, 1962; Martindale, 1989), Problem-Solving (e.g., Newell, Shaw, & Simon, 1962), Cognitive (e.g., Finke, Ward, & Smith, 1992; Schooler, Ohlsson, & Brooks, 1993) or Integrationist models (e.g., Simonton, 1999; Sternberg, 1999a), the essence of the creative act continues elusive. A lot is known about creativity, such as the occurrence of incubation and insight phenomena (Dunker, 1945), intuition and other meta-cognitive phenomena (Smith, 1995), and asymmetric distribution (Simonton, 1997); the effects of mental imagery (Rothenberg, 1979), verbal interference (Schooler & Melcher, 1995), and priming (Smith, 1995); and the role of personality (Eysenck, 1997), social context (Csikszentmihhalyi & Sawyer, 1995), prior knowledge, and domain specificity (Weisberg, 1995b). However, it has been hard to pinpoint the exact cognitive operations that account for creative capacity. This difficulty can be resumed in the creativity paradox introduced by Plato (quoted in Jowett, 1937) in his discussions with Meno about where new knowledge comes from. Put differently: How can a system produce ideas beyond the concepts that are already included in it? Where did Newton's conception of gravity come from? How did Schönberg get to his decatonal system? Plato's solution for this problem is that all new knowledge has to be a reminiscence, probably even from previous lives. Apart from the metaphysical character of this solution, any hypothesis that implies, like Plato's, drawing from a pool of existing ideas is faced with at least two problems. The first is that the scope of our knowledge would always be limited, and the second consists of the fact that it is unclear where this pool of knowledge came from in the first place.

Many authors have chosen a two-fold solution, proposing some kind of operation that generates ideas, followed by a second operation that selects the useful results from this generation process.

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This two-fold solution can be found in most major theories on creativity such as Campbell's (1960) blind variation and selective retention model; Mednick's (1962) associative hierarchy theory; Finke et al.'s (1992) geneplore model, and Davidson and Sternberg's (1986) three process theory of creativity.

In this article, I principally review and organize the possible cognitive operations in existing theories that generate new ideas or products. Only in the discussion section I offer some tentative reflections on the selection operation. Its main contribution is to demonstrate that existing theories on creativity can essentially be brought back to four creative cognitive operations. Special attention will be given to the abstraction operation, which has often been neglected the literature, though it constitutes a core operation for many instances of higher creativity. Finally, I demonstrate the relevancy of distinguishing these four operations with respect to the special–ordinary and the sudden-gradual controversies that exist in the field and research methodology. I shall begin by outlining some general aspects of creativity and by describing these two controversies.

Defining Creativity

There is no simple definition of creativity, but several emphases have been made in the past that highlight various aspects of the creative effort, both with respect to its process as well as to its product. Probably the most defining characteristic of creativity is that of novelty. To be creative means producing or thinking something new. Scientific or artistic creativity requires that something original is produced, or at least added, something that has not been conceived or made before. A scientific discovery, for instance, will not be deemed authorship if it has been published elsewhere before. When studying creativity as a cognitive function, originality for the individual alone is the only requirement. An individual that finds an original solution for a certain problem, unaware of the fact that this solution has been found previously by somebody else, is still considered a valid example of creativity. For instance, acts may be observed in children that are creative, yet are commonly performed by children in a certain developmental phase. New behavior in a subject that has been acquired by imitation or by verbal transmission will not classify as creative. A particular difficulty exists in defining this novelty criterion. From a certain perspective, every human act might be considered creative in the sense that no situation is exactly the same as a previous one. Even something as automatic as car driving requires constant adaptations to new traffic situations, and thus might be considered creative. Most calculus problems one encounters, one has never performed before, yet are solved by applying the same rules and operations. Although admitting that some creativity is involved in such situations, most authors prefer to differentiate between normal thought and creative thought, designating the latter as productive (Wertheimer, 1945), lateral (de Bono, 1970), or divergent thought (Guilford, 1986; Runco, 1991a). This distinction will be elaborated further in the special–ordinary controversy section.

A second defining characteristic of creativity is that its result should be adaptive (Simonton, 1999). Not just any variation or innovation can be considered creative unless the product is adaptive or useful to the goal it was designed for. An inventor who produces wild ideas, without any use or practical applicability, is rather judged insane than creative. According to Simonton, the creative effort does not exist in a vacuum but is appreciated according to practical or aesthetic standards. For instance, Edison's invention of the electric light may not be an example of extraordinary complex creation, but it is valued and remembered by its usefulness.

A third and final consideration about creativity is that some ideas or products can be considered more creative than others (Simonton, 1999). Some creativity impresses more than others, because some things are more radically or profoundly new than others Rembrandt made fabulous paintings, but remained largely within the existing tradition. Van Gogh, poorly understood in his time, paved the way for a new style. Mozart is probably one of the most gifted composers ever and took an existing tradition to its peak, yet Schönberg revolutionized music. Faraday has contributed greatly to the understanding of the unity of electricity and magnetism, yet after Einstein and Bohr, physics has never been the same. The distinction between important versus revolutionary contributions in science has been clarified by Kuhn (1962). He argued that most discoveries and theories occur within the current methodological framework of the scientific community, whereas few surpass the existing boundaries and assumptions. The ones that eventually cause paradigm shifts in their scientific field, when their ability to incorporate and exceed the existing paradigm is demonstrated. A similar reasoning can be applied to other, fields such as artistic, social, commercial, or interpersonal creativity (Gardner, 1983).

Although authors will generally agree on these defining characteristics of what is to be considered creative, this agreement does not extend itself to the question how creativity comes about. A lot of discussion has been going on around two key issues that will be outlined now.

Two Controversies

In studying creativity scientifically, two important approaches were developed, which Sternberg and Davidson (1995) referred to as the puzzle-problem approach and the "great-minds approach." The first is rooted in the Gestalt tradition. In 1926, Wallas published an influential process model for creative problem-solving, in which he proposed four phases: introductory work (preparation), a period of apparent inactivity (incubation), a sudden understanding (illumination), and, finally, elaborating and testing the idea (verification). Gestalt psychologists such as Wertheimer (1945) and Duncker (1945) saw a parallel between this illumination phase and the insight that occurs in the discovery of perceptual organization such as pattern recognition or figure–background switching. This led to a longstanding experimental tradition of investigating the creative process and measuring individuals' creative potential through the so-called insight problems (Sternberg & Davidson, 1995). Insight problems as opposed to analytical problems cannot be tackled by straightforward problem-solving. The solution strategies that first come to mind are not able to solve the problem. Insight problems can help to understand aspects of creativity, because their resolution process mimics phases of the creative process such as impasse, incubation, and insight. The value of these experiments was that they reproduced the phenomena that are characteristic elements of artistic and scientific creativity on a convenient laboratorial scale. Among these are the effects of priming and cognitive fixation (Smith, 1995), verbal interference in the incubation phase (Schooler & Melcher, 1995), the influence of hints (Burke, Mayer, & Hoffman, 1966), and the role of restructuring the problem (Gick & Lockert, 1995). An excellent collection of recent developments in this approach can be found in Sternberg and Davidson (1995).

The great-minds approach to investigating creativity studied characteristics of creative people and their products, elements largely drawn from biographical data and self-reports. One of the first and most famous in this line was Hadamard (1945); current representatives of this approach being Simonton (1886, 1997, 1999) and Weisberg (1986, 1988, 1995a, 1995b). Having the obvious disadvantages of nonexperimental research, this approach has nevertheless produced important data about the creative process. It has demonstrated the importance of imagery (Poincaré, 1945; Rothenberg, 1979), nonconformistic personality (Chambers, 1964), social context (Sternberg & Lubart, 1995; Csikszentmihhalyi & Sawyer, 1995), the role of prior knowledge and domain specificity (Mandler, 1995; Weisberg, 1995b), and intuition and other meta-cognitive phenomena (Smith, 1995).

From the confrontation of these two approaches, two controversies regarding the creative process arose, having very important implications for the understanding of creative capacity. The first controversy deals with the question of whether creativity should be understood as a gradual process in which solutions appear in a continuous fashion or as a discreet process in which the solution pops up in a single sudden leap. This is commonly known as the "sudden–gradual" controversy (Smith, Ward, & Finke, 1995, p. 328). The great minds approach has found evidence for a gradual process in often-reported meta-cognitive phenomena such as "feelings of knowing" or "warmth ratings" (Smith, 1995). Gruber (1974), studying the creative process in highly creative individuals, concluded that creation is a slow construction process. Simonton (1997) corroborated this finding, showing that it takes more than a decade to produce significant results in a scientific or artistic career. Arguments for the *sudden* hypothesis have come mostly from the Gestaltic puzzle-problem approach. It was argued that subjects first had to liberate themselves from functional fixedness (Duncker, 1945). This allowed for restructuring the problem (Wertheimer, 1945), which then led to immediate insight (Ellen, 1982; Scheerer, 1963). Crucial in this respect was the often-cited research by Metcalfe and colleagues (Metcalfe, 1986; Metcalfe & Wiebe, 1987), who found no evidence of feelings of warmth in insight problems, thus presenting a strong argument against the notion of creativity as a more gradual process. In Metcalfe's experiments, subjects could not predict their success on insight problems, whereas they could on routine algebra problems and trivia questions. Several attempts have been made to explain these findings without invoking a sudden insight. Perkins (1981), in studying retrospective reports, observed that the majority of subjects reported solving insight problems in a piecemeal stepwise fashion. He argued that the problem was solved in logical steps, but each step happened so quickly that they seemed to have occurred in a single leap. Similarly, Weisberg (1986, 1995a), studying the creative careers of various scientists and artists, argued that insight following restructuring was only one of the many crucial processes. He also identified combination of ideas, drawing analogies and outside influences, as an essential process, which together with restructuring make up a gradual process of shaping ideas or style: "There seems very little reason to believe that solutions to novel problems come about in leaps of insight. At every step of the way, the process involves a small movement away from what is known" (Weisberg, 1986, p. 50). Bowers, Farvolden, and Mermigis (1995) observed that incorrect answers or guesses in verbal insight problems often have a close semantic relationship with the correct solution. They argued that the suddenness of the appearance of insight represents an abrupt awareness of a mental state preceded by more continuous unconscious cognitive processes. Several attempts have been made to bridge this controversy by identifying some intermediate steps that lead to the restructuring of a problem. Davidson and Sternberg (1986) identified selective encoding, combination, and comparison as leading to insight, whereas Finke et al. (1992) found evidence of the existence of preinventive forms leading to innovative design.

The second controversy deals with the question as to whether ordinary, everyday creativity is governed by the same processes that are found in art and science or if they represent structurally different special capacities. Smith, Ward, and Finke (1995) refer to this issue as the "special–ordinary paradox" (p. 328). Advocates of the idea that the same processes are at work in all areas of creativity can be found mostly working within the puzzle-problem approach. Ghiselin (1952), for instance, found that renowned creators reported the same phases of hard preparatory work, incubation, insight, and verification of their ideas, as found in the process of insight problems. Thurstone (1952) found no qualitative differences in problem-solving at different levels of complexity. Novell, Shaw, and Simon (1962) simulated creative problem-solving in computer programs and concluded that creativity can be explained by ordinary processes, such as memory, algorithms, and inferential reasoning. Langly and Jones (1988) saw creativity as stemming from memory and thinking processes. More recently, Mandler (1995) defended that the ability to produce novelty is common in everyday thinking, suggesting that the mechanisms underlying creativity are normal ones. Schank and Cleary (1995) stated, "these small acts of creativity, though they differ in scope, are not different in kind from the brilliant leaps of Einstein" (p. 229). Finke (1995) specified processes that "can occur at many levels, ranging from major scientific theories and artistic creations to the simple, everyday activities" (p. 304). The most important arguments against this view came from authors that studied great creators. Vernon (1989) was strongly opposed to comparing ordinary creativity, such as a house owner designing his or her garden, with the creativity found in great artists such as Leonardo DaVinci. Treffinger (1987) viewed everyday creativity ("little C") as minor, compared to high creativity ("big C"). Dennis

(1955), Walberg (1988), and Vernon (1989) found arguments for differentiated creative abilities in the asymmetric distribution of creativity in the general population. A very small percentage of creators are responsible for the large majority of the important creative contributions. Although part of this effect may be explained by differences in motivation and opportunity, this finding constitutes a good argument that everyday creativity is probably not based on the same skills. Chase and Simon (1973), and later Simonton (1997), demonstrated that typically a period of 10 years is required for a scientist to make a major contribution to his or her field, and about 20 years to produce his or her most important work. It is questionable whether the cognitive processes involved in creativity, as found in yearlong endeavors of scientists and artists, are comparable with the processes involved in the solution of rather simple insight problems that generally do not require more than 10 or 15 min to be solved. Within the great-minds, approach Weisberg (1986, 1988) took a dissident position, arguing that insight should not be distinguished from other types of problem solving. He defend the idea that great creators basically do the same as everybody else, using regular cognitive skills such as imagery, language, and memory. I show later on that new light can be shed on these two controversies when both the demands of the task and the required creative operations are taken into account more accurately. These creative cognitive operations are now reviewed.

Creative Cognitive Operations

In this section, four different cognitive operations are discussed. Three of them (application, analogy, and combination) are generally mentioned in the literature on creative cognition, yet seldom properly distinguished from each other. A fourth operation, abstraction, can be found in the field of developmental and educational psychology (Thomas, Crowl, & Kaminsky 1996), yet rarely appears in the literature of creative cognition. The four operations, as will become clear by their description, represent an ordinal scale with respect to the amount of innovation involved in each type of creativity. Interestingly enough, the reference that comes closest to identifying these four operations in conjunction is over a century old. It is from William James (1880):

> But turn to the highest order of minds, and what a change! Instead of thoughts of concrete things patiently following one another in a beaten track of habitual suggestion, we have the most abrupt cross-cuts and transitions from one idea to another, the most rarefied abstractions and discriminations, the most unheard of combinations of elements, the subtlest associations of analogy. (p. 10)

Application of Existing Knowledge

A creative cognitive operation that is often mentioned in the literature on creativity might be identified as application: the adaptive use of existing knowledge in its habitual context. Creativity is required for fitting reality into an existing conceptual format. This operation consists of the creative adaptation of existing conceptual structures to fit normally occurring variations. The most obvious instance of application is everyday activity. Seemingly repetitious activities such as walking, driving, the use of language, and calculus all imply the application of known rules in a creative fashion. This operation is virtually identical to Sternberg's (1999b) "conceptual replication," which he defined as replication "under circumstances somewhat different from those that originally gave rise to it" (p. 92). I prefer the term *application* because it has a less mechanical connotation. The Gestalt tradition thought of this type of activity as noncreative. For example, Wertheimer (1945) distinguished this reproductive thought from the creative productive thought. Several authors have argued against this view of mechanically repeated action, arguing that everyday routine activity requires a considerable amount of creativity. For example, Mandler (1995) stated that "no repetition is very truly entirely that; there is always something novel in whatever we do or say" (p. 11). Schank and Cleary (1995) drew attention to the fact that no situation is exactly the same as a previous one: "The world is not full of standard problems amenable to standard solutions. Everybody needs to be somewhat creative simply to get through a typical day and deal with the innumerable shifts from the ordinary that arise" (p. 229). Even the simplest routine activity implies a certain recreation of cognitive structures, because no situation is exactly the same as previous ones. Application bears a strong resemblance to Piaget's (1936/1952) principle of *assimilation*. As opposed to *accommodation*, which implies a change in the organism's functioning to enhance adaptation to the environment, the principle of assimilation assumes that reality is formed and interpreted according to the existing cognitive structure.

In the realm of intellectual activity, a good illustration of application may be the work of a lawyer. The lawyer has to find the most advantageous fit between the facts present in the case and existing juridical concepts. This surely is a complex and creative task. Yet this creativity is limited in the sense that the lawyer cannot invent new concepts or laws, but has to work within the existing framework; no new conceptual structures are being created. Also, a considerable part of experimental and laboratorial scientific work can be considered application, because it is done within the existing framework introducing the necessary variations to adapt it to the necessities of the current context. Finally, in the realm of art, an example of application is craftsmanship: although basically the same product is produced with existing techniques, new adaptations are required continuously.

Analogy Detection

A second creative cognitive operation that is commonly identified is the use of analogy. Many authors have referred to analogy as a key concept in creativity. It implies the transposition of a conceptual structure from one habitual context to another innovative context. The abstract relationship between the elements of one situation is similar to those found in the innovative context. Michael Wertheimer (1991) virtually defined insight as analogy: "Discovery of the applicability of an existing schema to a new situation" (p. 190). Finke et al. (1992) also referred to analogical transfer as a generative process for creating preinventive structures. Weisberg (1995a) explained several artistic and scientific achievements by analogical transfer as follows: "situations in which information from a previous situation is transferred to the new situation that is analogous to the old" (p. 62). Analogy detection can be found in the three process theory of creativity of Davidson and Sternberg (1986; Sternberg, 1986) in the selective comparison phase, which involves the judicious use of analogies. Dunbar (1995), while studying scientists, identified three different kinds of analogical reasoning. *Local analogy* occurs when the scientist draws an analogy on a single characteristic from one experiment to another; in *regional analogy* a whole system of relationships from a similar domain is mapped onto another domain, and *long-distance analogy* is used when these systems come from an entirely different domain. Unlike the application operation, detecting and implementing an analogy is generally accepted as a creative act. It is seldom recognized though, that for this operation, in essence, no new cognitive structure is required! In both the application operation and the analogy operation, existing structures are used creatively. In the case of an application operation, they are used to deal with variations within the habitual domain; in the case of analogy, the existing knowledge is transferred to a new context. Most insight problems require solutions that are based on the use of analogy. A classification of insight problems (Weisberg, 1995b) showed that, in the large majority of these problems, the solution is either based on discovering an unconventional use of objects or words, or requires a loosening from the initial (most obvious) interpretation of the task. In these cases, the solution emerges from using the creative operation of analogy detection. This implies serious limitations for this methodology, an issue that will be addressed in the Discussion section.

An illustration of a scientific field in which the use of analogies is particularly frequent is chemistry. Numerous concepts such as bonds, shells, loadings, and energy are mere analogical approximations to model molecular interactions. Kékulé's (Wotiz & Rudofsky, 1954) famous discovery of the circular structure of the benzene model is another good example of creation by analogy. No new concept was required to solve the problem, because the concept of a circle was readily available. Other discoveries that are usually considered the result of analogical reasoning are Archimedes' crown (Davidson, 1995) and the planetary model of the atom (Finke, 1995).

In art, the importance of analogy can be found in the spreading of artistic styles like Impressionism or Surrealism. For instance, surrealism is based the idea of transcending everyday reality incorporating imaginative and unconscious elements (compare Breton, 1924). Having originated in literature (Breton; Soupault), it quickly spread to the visual arts (Chirico; Giacometti), music (Varèse), and film and photography (Buñuel; Man Ray). On an even bigger scale, the role of analogy can be seen in the spreading of the ideational content, for instance, during the Renaissance, which influenced virtually all areas of intellectual and artistic activity. Following a renewed interest in classical texts in Italy in the 15th century[1] (Holmes, 1989), the idea of importing classical values and methods, analogous to what happened in the visual arts and science (e.g., Donatello, Michelangelo, da Vinci), took place in fields such as music, philosophy, architecture, politics, law, and even warfare.

Combination Generation

Combination is the merging of two or more concepts into one new idea. It differs from analogy in the sense that this operation requires the creation of a new conceptual structure. Concepts can be combined either spatially—concepts are applied simultaneously—or temporally, in which the combination results from the sequential applications of existing ideas (Simonton, 1999). Mumford, Mobley, Uhlman, Reiter-Palmon, and Doares, (1991) added that combination can not only be obtained by the combination of previously distinct concepts, but also by the rearrangement of elements within an existing concept. Combination of ideas is probably the most frequently invoked mechanism for explaining creative ability. Maier (1940) argued that novel actions and approaches can be attained by old experiences in new combinations; Martindale (1989) stated that creative thought comes from new combinations of old ideas. Combination lies at the basis of Campbell's (1960) influential blind variation and selective retention model, in which the generation of new ideas results from a random combination process followed by an evaluation in which only the most useful ideas are retained. More recently, Simonton (1988b; 1992) elaborated this idea, introducing the concept of chance-permutations to clarify the variation step and drawing a link to Darwinism for explaining the selection mechanism to extract adaptive ideas from these permutations. Mednick (1962), within the associativist tradition, explained the concept of combination by the combination of remote ideas. Differences in creative ability can thus be explained by the steepness of the subject's associative hierarchy. Subjects with flat associative gradients more easily associate remote ideas and are more creative than subjects with steep associative gradients. Koestler (1964) found that creation in arts and science was obtained by sudden fusion of schemata. In the geneplore model of creativity, one of the generative processes identified by Finke et al. (1992) is *mental synthesis*, which is based on the combination of object parts, words, or concepts. Similarly, in their three-process theory of creativity Davidson and Sternberg (1986) proposed a selective combination process that is based on putting together the element of a problem in a way that previously has not been obvious to the individual. Scott et al. (2005) distinguished different two heuristics in arriving at conceptual combination: one involving feature extraction and mapping procedures[2], leading to better performance when a large number of element are presented, and another using case models, leading to better performance when few elements a presented.

[1]This is one of several competing explanations of where and when the Renaissance started, but these differences are not relevant for the point made here.

[2]Confusingly in the context of this article, Scott et al. refer to this as an *analogical approach*. This comes from the "analogical reasoning mechanisms" (p. 80) that are involved in discovering new combinations, specifically mapping features from one category onto another. This is different from *analogical transfer* I refer to, which leads directly to the creative end product. One thing are operations involved in procedures, strategies or heuristics that prepare for and lead (or not) to a creative solution. Another thing are the operations that are involved in the final creative step: the discovery of an innovative structure. I propose that operations involved in procedures towards creativity are many, but those that constitute the creative step itself, are few.

Finally, the combination operation is essential for concepts such as morphological synthesis (Allen, 1962), bissociation (Koestler, 1964), and conceptual combinations (Hampton, 1987).

An example of a scientific field in which combination thinking is predominant is engineering (Owens, 1969), both in its temporal and spatial variants. Many technical solutions are the result of bringing together existing elements in a useful and practical manner. An often cited example of scientific creativity is the discovery of the chemical structure of DNA (e.g., Gick & Lockhart, 1995; Weisberg, 1995a). This discovery is a good illustration of a combination operation. The double helix model resulted from combining existing building elements such as nucleotides, hydrogen bonds, and spiral lines into a single structure (Watson, 1968). In the realm of the arts, combination can be found in the influences artists have on each other, incorporating aspects of others' work into their own artistic styles. Maybe the most extreme example is Picasso, who vampirized other painters' work, first by imitating it and finally incorporating it into his own style (Miller, 1996).

Abstraction Discovery

A fourth creative operation that can be identified is abstraction. Although the previous three operations are specifically identified by a number of authors in the field of creative cognition, abstraction is generally not. Abstraction as a solution for the new knowledge paradox was first proposed by Piaget (1968) in his work on genetic epistemology. He distinguished *empirical abstraction*, focusing on objects, and *reflective abstraction*, in which the mental concepts and actions are the focus of abstraction. Young children primarily use empirical abstraction to organize the concrete external world, and increasingly use reflexive abstractions to organize their interiorized mental concepts. The underlying operation of "setting up a correspondence" (Piaget, 1968, p. 18) is the same for both types of abstraction. Piaget inferred that new abstract knowledge is built on top of other existing knowledge, so that new knowledge always depends on existing knowledge. He concluded that different levels of abstraction arise from the "transposition from one hierarchical level to another level"(Piaget, 1968, p. 18). In order to arrive at a formal definition of abstraction, it should be recognized that, linguistically, *abstraction* refers both to the mental process as well as the product of this process. The mental process of abstraction may be defined as the discovery of any structure, regularity, pattern, or organization that is present in a number of different perceptions that can be either physical or mental in nature. From this detection results the product abstraction: a conceptual entity, which defines the relationship between the elements it refers to on a lower, more concrete, level of abstraction. It may be helpful to give some examples to illustrate this definition. The first example is the acquisition of the notion of weight in young children (Piaget, 1972). Initially, young children only report the concrete experience of objects that are easy to lift and objects that are difficult to lift. From numerous physical experiences of heavy and light things, the notion of weight starts to emerge. In the beginning, the child will confuse weight with visual appearance, because usually bigger things are heavier and smaller things are lighter. From the repeated experience that some big things are light and some small ones can be heavy, a separate notion of weight starts to be perceived, independent of its concrete physical appearance. This is a new abstract notion that brings together the different experiences of graduations of heavy and light into one new concept of weight. A second illustration of abstraction is a classification example (see Figure 1). For dividing the six figures into two logical groups of three, several solutions are possible.

Three solutions are based on a concrete feature (big circles; small triangles; containing squares); in the fourth more abstract solution (inside figure equals outside figure) different concrete forms are grouped and the grouping criterion is derived from the relationship between the concrete features. In a small experiment that I conducted,

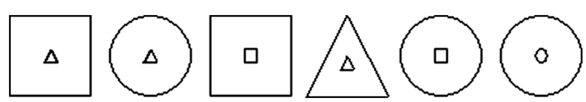

Figure 1. *Classification example: there are several ways to logically divide these six figures into two groups of three.*

88 out of 100 subjects first discovered concrete solutions and in the last place (or not at all) the more abstract solution. On a very basic level, abstraction can already be identified in the principles of perceptual organization, such as grouping and closure (Wertheimer, 1923/1950). In fact, it is a challenging hypothesis that these perceptual organizations may have formed the neurological matrix for abstraction in higher cognitive functions, analogous to Damásio's (1995) idea that systems for physiological monitoring, applied to mental processes, formed the basis for consciousness. Abstract representation is a prerequisite for several cognitive operations such as symbolization, classification, discrimination, generalization, and pattern recognition. It is not possible to classify objects or to recognize a pattern without the existence of an abstract criterion to determine class or distinguish a pattern. Margolis (1987) has taken this argument to the extreme point of view, that the entire cognitive repertoire of judgement and thinking is based on the capacity of identifying some type of regularity, pattern, structure, or coherence. A final consideration on the definition of abstraction is that by associating abstraction with the notion of pattern recognition and classification, an ambiguity may have been, unwittingly, introduced. What is traditionally understood by pattern recognition and classification are memory-based reproductive processes resulting from applying existing conceptual structures. These two operations would belong to the realm of the earlier mentioned application operation. What I refer to in this section are rather the operations of pattern discovery and class-creation through which new structures are formed through creative abstraction.

In spite of the importance of the notion of abstraction in developmental and educational psychology (Crowl, 1996) and in psychological assessment (Lezak, 1983), in the literature on creativity the notion seems to have been largely neglected. It seems that this is a striking example of segregation in scientific fields. Several authors on creative cognition can be found who distinguished abstraction operations but designated it with different terminology. A first instance can be found in James (1890/1950) citing Martineau (1879), when he discussed the act of comparison, which evokes abstract attributes. It is worthwhile reproducing part of this piece of 19th century prose:

> When a red ivory ball, seen for the first time, has been withdrawn, it will leave a mental representation of itself, in which all that it simultaneously gave us will indistinguishably coexist. Let a white ball succeed to it; now, and not before, will an attribute detach itself, and the color, by force of contrast, be shaken out into the foreground. Let the white ball be replaced by an egg: and this new difference will bring the form into notice from its previous slumber. (p. 486)

Mednick (1962) approaching creativity from an associativist perspective identified the abstraction operation distinguishing between creativity that results from association by similarity and creativity that results from association through a third mediating factor. He emphasized the abstract nature of the latter operation in arguing that this mediating factor is made up of common elements in the associated parts. He hints at the abstract nature of these elements when he states that association by similarity occurs in areas that are less dependent on symbols, whereas mediated association "is of great importance in those areas of endeavor where the use of symbols is mandatory" (Mednick, 1962, p. 222). Rothenberg (1979), in studying the relationship between creativity and dream phenomena in highly creative individuals, identified two processes that were reported frequently by both renowned artists and scientists. The first one is *homospatial thinking*, "the actively conceiving two or more discrete entities occupying the same space, a conception leading to the articulation of new identities" (p. 69). The second is *janusian thinking*, "actively conceiving two or more opposite or antithetical ideas, images, or concepts simultaneously" (p. 55). Both processes seem especially fit for abstraction discovery because they stimulate the discovery of the relationship between entities. In fact both operations are strikingly similar to the comparison experiment by Martineau (1879), mentioned earlier. The only authors who wrote extensively about the importance of abstraction in creativity are Root-Bernstein (1991) and Root-Bernstein and Root-Bernstein (1999). They amply discussed the role of abstraction, or *abstracting* as they called it, in many examples of scientific and artistic creativity. Root-Bernstein (1991) approached abstraction as a process of simplification and ''elimination of unnecessary detail to reveal underlying order, pattern or structure'' (p. 87). In discussing some works of abstract art, Root-Bernstein and Root-Bernstein (1999) gave the impression that the process of simplification and stripping of detail lead to the discovery of abstraction. I think that it is more correct to state that structure, that is, the relationship between entities, once discovered can be more clearly demonstrated in a simplified representation leaving out unnecessary detail. It is not very likely that a strategy of random stripping of details will easily reveal underlying structure. Explicit reference to the role of abstraction in creativity can be found in Ward, Patterson, and Sifonis (2004), who demonstrated that encouraging abstract ways of formulating creative generation tasks results in increased originality. A similar result was found earlier by Jansson, Condoor, and Brock (1993) with respect to engineering design tasks. Also, Vandervert et al. (Vandervert, Schimpf, & Liu, 2007; Welling, 2007) linked creativity to abstraction, proposing that the cerebellum might have an important role in innovative thought through its capacity of abstracting the dynamics of both movement and thought.

Scientific fields in which abstraction plays an important role are biology, physics, and mathematics. A good example of scientific innovation that results from abstraction is Einstein's (1905) relativity theory. In his theory, the relation between time and space is redefined into a new higher abstraction in which time and space are part of the same entity. Another example is Darwin's (1859/1964) theory on evolution. Darwin explained his observations of diversity of characteristics within species, introducing a new abstraction: evolution of species through the higher survival rate of the specimens possessing the most adaptive characteristics. Dawkins' (1976) refinement—introducing the concept of survival of genes rather than the survival of individuals in order to explain altruistic tendencies—is yet another example of abstraction. Gould (2002) contested this exclusive reliance on selection and emphasized the role of chance and environmental factors in evolution. Gould's contribution does not introduce a new abstraction, but is a good example of a combination operation. Two existing concepts, selection and chance factors, are combined into a useful new one. In the field of the arts, the abstraction operation can be illustrated by the transition from figurative to abstract painting as can be found in the work of Braque, Rothko, and Mondriaan. Another example is the development of an entirely new personal language, such as can be found in the work of Bartok, Miró, and Van Gogh.

Discussion

The four mental operations presented above are theoretically exclusive, but in practical terms their distinction may sometimes be difficult. It may be difficult to know if a creator arrived at a particular solution through analogy, or if his or her discovery was the result of an independent abstraction operation whose similarity with an existing concept elsewhere was discovered only later. Simonton (1987) for instance, shows that simultaneous discovery (multiples) is quite a common phenomenon and often it is difficult to establish if the authors had knowledge of each other's progress. Another fact that may complicate distinguishing one operation from another is that many creative products are the result of the use of more than one operation. Weisberg (1995a), for instance, showed that many creations are the result of a stepwise process of progressive ''discontinuities'' (p. 60). These four operations form an ordinal scale, with innovation increasing from application to abstraction. In the application operation, an existing structure suffers minor adaptations in habitual context; in the analogy operation existing a structure is transferred to an innovative context; in the combination operation existing structures are combined to form a new one; and, finally, in the abstraction operation a new structure is formed, defining the relationship between existing structures. However, one should keep in mind that none of the mentioned operations generate entirely new knowledge because the result is always dependent on, or constructed with, previous knowledge. It may be tempting to assume that the ideas that result from abstraction are also the ones that are most impressive or revolutionary, but this is not the case. For example, a great scientific and social revolution was the introduction of the heliocentric planetary movement

(Miller, 1996). Because the idea of circular motion was already present in the geocentric conception, no particularly brilliant feat, but rather courage, was required to arrive at this idea. The heliocentric worldview constitutes a mere analogy of the geocentric view. Sternberg (1999b), in his propulsion model, distinguished seven different types of impact that creative contributions may have on a domain, varying from *replication* on one end of the scale to *reinitiation* on the other. Originality and importance are of a different order; an idea being revolutionary or not depends on its relation with the already existing ideas in a domain.

Distinguishing these four operations may shed some new light on the two controversies described above. With respect to the sudden-gradual controversy, as outlined, defenders of the gradual position derived their arguments mainly from biographical studies of creators who report feelings of warmth, while authors that focussed on insight problems defended a process of sudden discovery in which meta-cognitive phenomena play no role. The explanation of their contradictory observations may be that in each situation, different cognitive operations are involved. Csikszentmehalyi and Sawyer (1995) suggested that there may exist two types of creative insight, one characteristic of a short time-frame process and another of a "long time-frame process." The task demands of insight problems and the task demands of scientific or artistic creations are quite different. Because of experimental convenience, insight problems are rather easy to solve and cannot reasonably be compared with issues like the Fermat problem or the creative leap in color use in Van Gogh's painting. Insight problems are not solved immediately because the subject is led in the wrong direction, for instance, by infrequent word use or another type of suggestive instruction. After restructuring the problem, the solution is rapidly found by using ordinary problem-solving skills requiring just an application operation. An example of such a problem is the nine-dot problem (Duncker, 1945). In another type of insight problem, the solution requires the uncommon use of objects, with the subject being led astray by the object's ordinary use that comes to mind first. An example of this type of insight problems is the pendulum problem (Maier, 1931). The cognitive operation thus typically required to solve this kind of problem is the analogy operation.

Scientific and artistic creations typically require deep reconceptualization that results from combination or abstraction operations. These operations represent long time-frame processes of many years, in which solutions are intuitively pursued until becoming verbally explicit (Welling, 2005). Looking at the complete oeuvre of Mondriaan or Escher and following their productions chronologically, there seems to exist a natural sequence that is easy to detect post-hoc. It is as if the artist has been working towards his final product. Of course, the artist could not foresee his final work, but some prospective process must be at work to produce this gradual progression. This may explain why products of a long time-frame that result from combination and abstraction operations are accompanied by feelings of warmth, whereas insight problems that are generally products resulting from short time-frame processes such as application or analogy operations are not. With respect to the special–ordinary controversy, identifying these four different creative operations basically provides arguments for the defenders on the special side. It seems that so-called high creativity is more readily associated with combination and abstraction operations, while everyday creativity is derived primarily from application and analogy operations. Some contradictory findings might be explained by the fact that high creativity is often not the result of a single operation, but results from a longer period in which several operations are put to use during the discovery process. The fact that essentially different processes may be at work in solving insight problems and in scientific or artistic creativity has implications for the validity of psychological assessment through insight problems. The fact that relatively simple insight problems can be predictive of (high) creative potential is understandable, because they measure the important capacity for divergent thinking to overcome cognitive fixation. They cannot measure the person's ability to put to good use combination and abstraction operations, ask the right questions, intuition for fruitful directions, persistence, and other important aspects that make up the complex issue of a successful creative career.

Different methodology is required to study the full range of creative cognitive operations experimentally. Researching creativity with the traditional methodology of insight problems, on the one hand, hardly goes beyond application and analogy operations. Self-reports from highly creative people, on the other hand, lack experimental rigor. Some recent studies have used methodologies that seem more appropriate to study both short and long time-frame processes. Examples are Getzels and Csikszentmihhalyi's (1976) longitudinal study on problem-finding; Finke et al.'s (1992) research on preinventive forms; Dunbar's (1995) longitudinal study of real scientists working on their own research, and Mumford's social innovation problems (Scott et al., 2005; Hunter et al., in press).

In the introduction, I mentioned that most authors adopted a two-step model—generation of new ideas, followed by the selection of adaptive ideas—to describe the creative process. The four creative operations refer essentially to the first step of this process. The second step has received less attention in the literature (Runco, 1991b). The generation of new ideas does not guarantee their usefulness. For instance, Schank and Cleary (1995), while simulating the creation of inferences by a computer program, found that a combinatorial explosion occurred that "drowned relevant inferences in a swamp of irrelevant ones" (p. 233). Simonton (1999) related the usefulness of an idea to its evolutionary or adaptive value. This statement may be quite clear for inventions such as the wheel or gunpowder, but less obvious for theoretical science or artistic works. Miller (1996) argued that our capacity to select may come as a sense of beauty: "intuition and aesthetics come into play to weed out certain combinations" (p. 335). Although this description may come close to how many people actually experience a selective process, it is not very helpful for understanding its mechanism of functioning. Runco (2003) argued that selection does not only occur after idea generation, but is inextricable from ideation. Damásio (1994) in his work on the primacy of emotion, presented some proof that this selection device actually exists on a neurological level. In a patient with a very specific frontal lobe lesion, no intellectual deficit could be determined through ordinary cognitive assessment. Yet he was unable to give a normal direction to his personal and professional life. Damásio concluded that the patient's deficit resided in the inability to distinguish relevant from nonrelevant information. The patient would produce an enormous amount of solutions for such a simple problem as a new doctor's appointment, taking almost every possible consideration into account, unaware of the futility of this extensive effort. Damásio (1994) proposed that humans possess an emotionally based selection tool that he calls a "somatic marker" (p. 165). This idea of relevancy of information may be an important clue for further studying the selection mechanism. In some cases, relevancy may be measured by its survival value, in other cases by aesthetic criteria, but in every task, implicit selection criteria are present that determine what is an acceptable or good solution. Even while solving the pendulum problem, the respondent somehow knows that "ask the extraterrestrial to hand me the cord" is not the intended answer. Throughout the creative process, the creator uses the implicit criteria to select what ideas to pursue. For example, in an engineering problem, there may exist unstated selection criteria for size or cost of the proposal. Artistic productions are supposed to demonstrate originality and not imitation, yet the creator may keep in mind that distancing too far from contemporary style may lose the public's interest. In scientific creations, in principle, practical use would be less of a requirement than in engineering problems, but there may exist criteria for comprehensiveness and elegance. Successful creators are probably well aware of this required structure and it may be quite revealing to study these criteria.

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