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Abstraction promotes creative problem-solving in rhesus monkeys

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ABSTRACT

Abstraction allows us to discern regularities beyond the specific instances we encounter. It also promotes creative problem-solving by enabling us to consider unconventional problem solutions. However, the mechanisms by which this occurs are not well understood. Because it is often difficult to isolate human high-level cognitive processes, we utilized a nonhuman primate model, in which rhesus monkeys appear to use similar processes to consider an unconventional solution to the difficult reverse-reward problem: i.e., given the choice between a better and worse food option they must select the worse one to receive the better one. After solving this problem with only one specific example—one vs. four half-peanuts—three of four monkeys immediately transferred to novel cases: novel quantities, food items, non-food items, and to the choice between a larger, but inferior vegetable and a smaller, but superior food item (either grape or marshmallow), in which they selected the inferior vegetable to receive the superior option. Thus, we show that nonhuman animals have the capacity to comprehend abstract non-perceptual features, to infer them from one specific case, and to use them to override the natural preference to select the superior option. Critically, we also found that three monkeys had a large learning and performance advantage over the fourth monkey who showed less generalization from the original one and four half-peanuts. This difference suggests that abstraction promoted problem-solving via cascading activation from the two food item options to the relation between them, thus providing access to an initially nonapparent problem solution.

1. Introduction

It is impossible to encounter truly identical situations. The Greek philosopher Heraclitus recognized that the natural world is too dynamic and varied to step in the same river twice, as the particles that constitute it are always in motion. In face of this challenge, we discern regularities beyond the specific incidents we encounter. These regularities arise from inductive abstraction processes that generalize specific events, enabling us to process novel experiences efficiently and react accordingly (Holyoak & Morrison, 2012). Moreover, such inductive processing occurs at multiple levels of abstraction, allowing us to identify a novel sensory input as an instance of, for example, a known object, category, concept, or relation (Badre, Hoffman, Cooney, & D'Esposito, 2009; Herrnstein, 1990; Holyoak & Morrison, 2012; Kowaguchi, Patel, Bunnell, & Kralik, 2016; Kralik, 2012; Kralik & Hauser, 2002; Rosch, 1978; Tenenbaum, Kemp, Griffiths, & Goodman, 2011).

Abstraction also has the power to promote creative problem-solving. Although creativity is difficult to define, it is important to distinguish noncreative and creative problem-solving. Problem-solving in general entails generating a representation of the problem and then solving it by determining the proper sequence of actions to reach the goal state (Bassok & Novick, 2012). Creativity can be introduced into the problem-solving process in one of two places: either in the formulation of the problem itself, or in the delineation of the path taken to solve it. Although there has been considerable research progress examining how agents find solution paths when faced with relatively well-defined problems, less is known about how problem representations are generated and updated (i.e., restructured) (Bassok & Novick, 2012; Sutton & Barto, 1998; van Steenburgh, Fleck, Beeman, & Kounios, 2012). We therefore have focused on the mechanisms of problem formulation and the use of creativity therein.

The curse of dimensionality in real-world problems necessitates a selection process: typical problem-solving involves considering only the most apparently relevant factors to represent the problem. It is up to the observer to determine which factors facilitate a solution. For example, to find a new path to a restaurant one normally considers the most obvious means of transportation (e.g., walk, subway, car), and will take

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the most direct route available; these solutions are in turn bound by the factors of cost, availability, and intended effort. In contrast, creative problem-solving entails consideration of *nonapparent* problem components, which at first pass means those outside the scope of the original problem representation: i.e., those not as salient, directly relevant, or learned from experience (Cheng, Ray, Nguyen, & Kralik, 2013; Kralik, Mao, Cheng, & Ray, 2016; Kralik, Shi, & El-Shroa, 2016; Smith & Ward, 2012). A classic example with humans is the 9-dot problem, in which nine dots are displayed in a 3 × 3 square matrix, and the participant must connect all nine dots by drawing only four lines without lifting the pen/pencil (Cheng et al., 2013; Maier, 1930; van Steenburgh et al., 2012). In this case, the highly salient dots and most direct lines that begin and end at the dots define the *apparent* problem formulation, whereas a solution can only be found when one realizes that the lines can extend past the dots (*nonapparent* formulation). Thus, in creative problem-solving, an inadequate formulation of the problem based on apparent factors must be replaced by considering 'outside-the-box' components (Kralik, Mao, et al., 2016; Kralik, Shi, et al., 2016; Smith & Ward, 2012; van Steenburgh et al., 2012).

Abstraction provides a means to rediscover these nonapparent possibilities: e.g., when one abstracts from a particular instance to a larger class, more instances become available from which a potential problem solution can be identified – a specific-to-general-to-specific access route (Smith & Ward, 2012; Ward, 1994; Ward, Patterson, & Sifonis, 2010; Ward, Patterson, Sifonis, Dodds, & Saunders, 2002; Ward & Sifonis, 1997). However, in principle, abstraction could be even more powerful by leading to further cascades of activation beyond the additional specific instances of the given class: e.g., from specific instances to general class to *relations* with other classes. Unfortunately, it is difficult to find clear cases of this directed cascading effect of abstraction on problem-solving ability in the human problem-solving literature. This is so because it is sometimes difficult to tease apart the underlying processes and problem obstacles, such as in the 9-dot problem where, for example, blocking (e.g., by the salient dots) or remoteness (e.g., considering all points on the page) could both underlie the difficulty. The investigation of creative cognition in nonhuman animals provides a complementary approach that may help to isolate and characterize the fundamental underlying cognitive mechanisms (and if successful, the subsequent ability to study neural mechanisms in greater detail). Although human creativity far exceeds that of other animals, the processes by which nonapparent components are accessed once problems become sufficiently challenging may be shared across broader animal clades, enabling nonhuman studies to help delineate these processes.

To investigate how abstraction may promote creative problem-solving via the cascading activation process, we utilized the *reverse-reward* problem with rhesus monkeys (*Macaca mulatta*), in which the monkeys are offered a choice between a less-preferred and more-preferred option, such as one and four quantities of the same food, but are given the option they do not select (Fig. 1A). Thus, they must select the less-preferred option in order to receive the more-preferred one (Albiach-Serrano, Bugnyar, & Call, 2012; Albiach-Serrano, Guillen-Salazar, & Call, 2007; Anderson, Awazu, & Fujita, 2000; Anderson, Awazu, & Fujita, 2004; Boysen, Berntson, Hannan, & Cacioppo, 1996; Boysen, Mukobi, & Berntson, 1999; Genty, Chung, & Roeder, 2011; Genty, Palmier, & Roeder, 2004; Kralik, 2005, 2012; Murray, Kralik, & Wise, 2005; Shifferman, 2009; Uher & Call, 2008). Although trivial for humans, this problem is difficult for nonhuman animals — e.g., rhesus monkeys require roughly 1000 trials to solve it (Chudasama, Kralik, & Murray, 2007; Murray et al., 2005). It has generally been assumed that the difficulty stems from the lure of the better reward. However, evidence suggests that this is often not the key issue. First, when choosing between a larger and smaller quantity most subjects inhibit the selection of the larger quantity relatively quickly; however, instead of selecting the smaller quantity, they switch to a side bias (e.g., repeatedly selecting the left option), thus reaching an extended impasse prior to spontaneously solving the problem (Chudasama et al., 2007; Murray et al., 2005). This extended impasse and spontaneous problem-solving suggest additional confusion with the task that is eventually overcome (Kralik, Mao, et al., 2016; Murray et al., 2005). Second, to test the issue of self-control directly, Kralik (2005) first posed an even simpler version of the reverse-reward problem to cotton-top tamarins (*Saguinus oedipus*), a New World monkey, in which when given a choice between 1 and 3 food items, selecting the 1-item option yielded the 3 item-option, but selecting 3 yielded nothing (Fig. 1B). The tamarins were unable to solve this problem even with the strong punishment of receiving nothing when selecting the larger quantity. It was then reasoned that if the problem stemmed from a lower-level impulse to select the larger quantity over the smaller one, the difficulty should continue regardless of any change in outcome as long as the original offer, 1 vs. 3, remained the same. Moreover, if anything, the task should become more difficult if the reward outcome for selecting the smaller quantity was *reduced* from receiving three food items to receiving, e.g., only one, with reward thus three times smaller (Fig. 1C). Nonetheless, when keeping the offer the same (1 vs. 3) but reducing the reward outcome for selecting the single quantity from three to one, all four subjects solved the problem, selecting the smaller quantity over the larger one, suggesting that the difficulty lay more in the complexity of the task rather than in the inability to inhibit selection of the larger quantity. The Kralik (2005) study suggests that a critical difficulty in solving the reverse-reward problem stems from the interaction between the two choice options: that is, in recognizing the *tertiary relation* between the food items (i.e., relation between two things other than oneself). This interpretation is supported by findings from other studies such as the ease with which chimpanzees solve a related accumulation task, in which they readily learn to select a single marshmallow over an accumulating bowl of marshmallows if the chimpanzees directly see that when they select the single marshmallow it is then placed by the experimenter in the bowl (which subjects will ultimately receive) (Beran, James, Whitham, & Parrish, 2016).

Additional studies have also shown that in multiple cases where problem-solving difficulties have been assumed to reflect lower-level (e.g., Pavlovian) influences, they may more accurately resemble cognitive illusions that reflect the constraints/biases of a simple problem-solving system rather than affect-driven prepotent responses (Kralik, 2017; Kralik, Shi, et al., 2016; Santos, Ericson, & Hauser, 1999; Wallis, Dias, Robbins, & Roberts, 2001). Indeed, the discontinuous reverse-reward learning curve for rhesus monkeys suggests that, after the extended side-bias impasse, the spontaneous solving of the problem does not occur via simple gradual strengthening over trials, but rather, some change that provides access to the previously inaccessible nonapparent solution (Chudasama et al., 2007; Kralik, Mao, et al., 2016; Murray et al., 2005). In this light, reverse-reward problem-solving by nonhumans provides a model to study the mechanisms used to find nonapparent solutions, ones that may be shared by people to access remote possibilities that lead to creative solutions. It has in fact been theorized that the ability to solve nonapparent problems may be the key functional advance with the evolution of granular prefrontal cortex in primates (i.e., lateral and frontal polar cortex) (Kralik, 2017; Kralik, Mao, et al., 2016; Kralik, Shi, et al., 2016; Passingham & Wise, 2012; Preuss, 1995; Striedter, 2005; Wise, 2008).

To utilize the reverse-reward problem to investigate how abstraction may promote problem-solving via a cascading activation process, we leverage the fact that in cases where nonhuman subjects learn to solve the reverse-reward problem with the food items present, their solution could be based on a number of different levels of abstraction: e.g., the specific quantities and food items in training (e.g., one and four food pellets), or something more abstract such as the number of items. Previous studies have found evidence for a more general *number* or *size* based solution (Albiach-Serrano et al., 2007; Anderson et al., 2000, 2004; Boysen, Berntson, & Mukobi, 2001; Genty et al., 2004, 2011; Kralik, 2012; Uher & Call, 2008). For example, rhesus macaques spontaneously generalized to novel quantities after learning the task