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An explicit cue improves creative analogical reasoning

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ABSTRACT

Creativity is likely to be related to intelligence, though the nature of this relationship remains largely unresolved and few studies have examined creativity in the context of measures traditionally related to intelligence. Like intelligence, creativity has often been studied as a static trait or as subject to change over long durations through training or education. By contrast, creativity as a dynamic state, particularly as a state that is subject to conscious augmentation within short time durations, has been less well-studied. Here, we tested the hypothesis that performance on a task of creative intelligence (creative analogical reasoning) can be improved through the deliberate effort to be creative. Specifically, we tested whether an explicit cue to "think creatively" would elicit better identification of creative analogies among 40 participants performing a four-term verbal analogical reasoning task. Consistent with our hypothesis, on creativity cue trials, the participants were 1) more likely to accurately identify highly creative analogies as valid, and 2) no more likely to inaccurately identify false analogies as valid. This pattern of results indicates that, consistent with a widely accepted standard for measuring creativity, the cue was successful in eliciting responses that were not only novel (divergent) but were also appropriate (bounded by task constraints). The findings show, in a within-subjects design, that deliberately attempting to augment creative state can enhance performance on a reasoning task with objective criteria. These findings are discussed with respect to the state vs. trait distinction in creativity and likely neural mechanisms of creative reasoning.

1. Introduction

While creativity can be difficult to operationalize, cognitive research has identified some factors that contribute to creativity in reasoning. For example, in analogical reasoning (e.g., Puppy is to Dog as Spark is to Fire), the surface-level dissimilarity, or semantic distance, between the items being compared (e.g., the semantic distance from [Puppy:Dog] to [Spark:Fire]) is a key factor in determining the creativity of analogical connections (Costello & Keane, 2000; Green, Fugelsang, Kraemer, & Dunbar, 2008; Holyoak & Thagard, 1995; Sternberg, 1997). Furthermore, a consensus has emerged that creative connections must have two primary characteristics in order to produce usable innovation: novelty, a characteristic reflected by divergence or unusualness, and task-appropriateness, a characteristic reflected by fitting production to relevant constraints (Mayer, 1999; note that quality, or the characteristic of being compelling, is often considered a third defining characteristic of creativity). Although novelty alone is sometimes informally considered a rough equivalent of creativity, task-appropriateness is necessary in order to make novel, semantically distant connections usable (Mayer, 1999; Sternberg, 1997).

Analogical reasoning requires generating novel relations (mappings) that draw a connection between previously unconnected concepts or situations (e.g., generating a mapping between [Puppy:Dog] and [Spark:Fire]). Analogical relations

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are referred to as second-order relations because they are relations between relations. Successful analogical reasoning requires generation of mappings that are not just novel, but that also fit the constraints imposed by the specific terms used in the analogy. In particular, the first-order relations on the respective sides of the analogy (e.g., the first-order relation between Puppy and Dog, and the first-order relation between Spark and Fire) impose constraints on appropriate mappings. Ignoring the constraints of the first-order relations (e.g. generating a mapping based on the child to parent relationship of Puppy:Dog that does not fit the constraints of the Spark:Fire relation) would not lead to a useful mapping. Thus, analogical reasoning represents a good case of novel generation (of mappings) with prominent constraints of task-appropriateness.

Evidence from science, education, and industry indicates the effectiveness of analogical reasoning as a means of directing and constraining creative connections for innovative outcomes (Costello & Keane, 2000; Dahl & Moreau, 2002; Holyoak & Thagard, 1995; Schunn, Paulus, Cagan, & Wood, 2006). Reasoning by analogy has proved to be an especially useful tool in the sciences, helping scientists explain and find new solutions for unexpected issues that arise in their research (Dunbar & Blanchette, 2001). Creative analogies that bridge great semantic distances, as when Harvey likened the heart to a water pump, have repeatedly demonstrated the potential to spark innovative leaps of scientific advancement (Dunbar & Blanchette, 2001; Holyoak & Thagard, 1995). However, despite the considerable value of creative analogical reasoning, studies of reasoning have not examined parameters directly related to creativity (e.g., semantic distance). Likewise, studies of creative thinking have typically been constructed without the constraints of a reasoning task, and have instead focused on the novelty/divergence component (Carlsson, Wendt, & Risberg, 2000; Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005). Thus, an important topic for both creativity and reasoning research is creative integration of semantically distant concepts in the service of reasoning.

1.1. Can creativity be cued?

Much research on the construct of creativity has been devoted to the measurement of creativity as a static trait, an intrinsic ability that some have and others do not. For instance, Guilford's theoretical framework (Guilford, 1950, 1967), and the prominent Torrance Tests of Creative Thinking (Torrance, 1966) are based on measurement of creativity as a stable trait quality, similar to IQ. A great deal of empirical work has also been done to characterize the effects of long-term training or educational programs on creativity over the course of development or long periods within adulthood (Pirkko, 1975, and see Rose & Lin, 1984, and Scott, Leritz, & Mumford, 2004, for reviews). Major research initiatives have sought to bolster creativity in the classroom environment to foster innovation through education (e.g., Schunn et al., 2006).

While these lines of research are still active, several investigations have emerged recently which are directed at the question of creativity as a dynamic state (e.g., Amabile, 1996; Dai & Renzulli, 2008; O'Hara & Sternberg, 2001). A central issue within the emerging dynamic creativity literature concerns the effect of explicit cues to be creative. Amabile (1996) posits that motivation to be creative may be "the most important determinant of the difference between what a person *can* do and what he *will* do." However, Amabile theorizes that only extrinsic cues that produce an intrinsic motivation to think creatively will have a beneficial effect; cues that make extrinsic motivations (e.g., money) more salient may actually impair creativity because they are perceived as controlling or intimidating. Other work has demonstrated more specifically how extrinsic cues to think creatively can enhance performance. For instance, O'Hara and Sternberg (2001) found that groups of participants who received an explicit cue to be creative wrote essays that were more creative than a control group that did not receive the creativity cue. This evidence is bolstered by several other reports of improved performance on creativity measures in between-subjects designs that varied the explicit instructions given to separate groups (e.g., Harrington, 1975; see Chen et al., 2005, for a more complete review). However, because these studies have all employed between-groups designs, they have not been able to test whether creativity is a dynamic state in the sense of being heightened and lessened within an individual across time. Further, these studies did not measure the effect of increased creativity on reasoning.

A small number of studies have examined dynamic creativity using a within-subjects paradigm. One early study by Gilchrist and Taft (1972) showed some evidence for facilitation of originality when participants were instructed to "be original." However, the findings of this report were highly confounded by order effects, as the creativity condition always followed the same neutral condition, and thus are difficult to interpret. Three more recent studies have examined within-subjects effects of explicit instructions in creativity-related tasks (Abdullaev & Posner, 1997; Howard-Jones et al., 2005; Seger, Desmond, Glover, & Gabrieli, 2000). However, these studies focused primarily on changes in neural activity; only one of these actually measured the creativity of participants' responses to determine whether the instructions had an effect on behavioral performance (Howard-Jones et al., 2005). These authors used a within-subjects paradigm that included a story-writing task, and cued subjects to either be creative or be uncreative on different trials. Stories generated under the creativity cue were in fact rated to be more creative. This study provided an initial demonstration of within-subject effects of a creativity cue; however, it did not address effects on reasoning. Further, this study was limited in that only eight participants were included and, because of the lengthy nature of a story-writing task, only a relatively small number of trials were possible per individual. In addition, Howard-Jones et al. relied on subjective ratings to assess the creativity of responses. This is a commonly used method of assessing creative performance, but it allows less measurement precision than an objective index.

1.2. Can a cue improve reasoning?

Like creativity, reasoning ability has often been viewed as a static trait, and is generally considered a major component of trait intelligence as measured by standardized intelligence tests (e.g., Raven, Raven, & Court, 1998; Roid, 2003; Wechsler, 1997; Woodcock, McGrew, & Mather, 2001). However, based on between-subjects research, there is some empirical indication

that reasoning ability may be somewhat dynamic and can be influenced by explicit cues. For instance, Gick and Holyoak (1980) found that a group of participants who received no explicit cue performed poorly on an analogical transfer task in which a target problem could be solved by drawing an analogy to a previously exposed story. However, in a group that received an explicit hint to consider the previously exposed story when generating solutions, 30% more subjects were able to generate the optimal solution to the target problem (Gick & Holyoak, 1980). Chen et al. (2005) found that mathematical problem-solving performance benefited from explicit cues to think creatively in a between-subject design. This somewhat unexpected finding in a mathematics task not typically associated with creativity provides support for possible benefits of creativity cues for reasoning.

1.3. The approach of the present investigation

In the present investigation, we examined analogical reasoning using verbal propositional analogies of the basic form A is to B as C is to D. These analogies were classified as "cross-domain" (more creative) or "within-domain" (less creative) by a group of 84 raters. The experimental task we employed is somewhat unusual for a creativity paradigm in that it does not require overtly producing new words or images. The creativity involved in the present analogical reasoning task was in mentally generating analogical mappings between a word-pair presented on the left of a computer screen and a word-pair on the right (Fig. 1). These mappings were not explicitly available to participants, but rather participants had to come up with mapping(s) that validly connected the two word-pairs. Although generation in this task was covert, rather than overt, it may nonetheless be considered a form of creative generation. Creative ideas can be (and often are) generated without being overtly expressed. Further, we have obtained evidence in recent brain-imaging investigations of creative analogical reasoning that demonstrates strong similarity between the analogy evaluation task used in the present study and a task of overtly generating solutions to open-ended analogies (Green, Fugelsang, Kraemer, Gray, & Dunbar, 2010, 2012; see Discussion).

Investigating individuals' ability to "turn on" creative reasoning processes deliberately and over short durations, has important implications for education research and teaching strategies. As noted above, few previous studies of creativity or reasoning have examined variation in performance within an individual across time, especially over short durations.

Here, we hypothesized that analogical reasoning in our experimental task would be affected by changes in creative state because good performance depended on subjects mentally generating creative mappings. Importantly, these mappings had to be both novel (they had to connect semantically distant word pairs to form creative analogies), and task-appropriate (they had to fit the four-word sets, and four-word sets that did not support valid mappings had to be identified as such). We tested whether an explicit creativity cue would enhance creative analogical reasoning without undermining appropriateness. Specifically, we compared participants' analogical mapping for creative analogy stimuli on creativity cue vs. non-cue trials.

2. Methods

2.1. Subjects

40 undergraduate native English speakers at Yale University (22 females and 18 males, aged 20 ± 1.4 years) took part in the investigation for course credit. Informed written consent for all participants was obtained prior to the experiment. All procedures were approved by the Yale University Human Investigation Committee.

2.2. Materials and procedure

Stimuli were four-word sets, comprising a word-pair on the left and a word-pair on the right, such as 'Kitten:Cat:: Spark:Fire' arranged in a rectangle as in Fig. 1 (see Green et al., 2010, for a full listing of the stimuli used). On each trial, the participants indicated whether the four-word set constituted a valid analogy (left word-pair analogous to right word-pair), responding 'true' or 'false' by key press with the index or middle finger of the right hand. Four-word sets appeared in one of two colors, purple (non-cue) or green (creativity-cue). The participants were instructed that "When the words appear in green, think more creatively about whether the four-word set constitutes a valid analogy." We obtained a semantic distance value for each analogy item using latent semantic analysis (Landauer & Dumais, 1997; Landauer, Foltz, & Laham, 1998). In particular, pairwise comparisons were made between the word pairs constituting the left and right halves of each analogy.

The latent semantic analysis application (http://lsa.colorado.edu) calculates the similarity between the contextual-usage meanings of words as measured by the cosine of the included angle between vectors assigned to those words within a very high-dimensional "semantic space," comprising extensive corpora of English text. A vector is added for multiword inputs such as the word pairs constituting our analogy stimuli. In addition, 84 independent raters provided a binary rating for all stimuli in order to separate them into two types: cross-domain analogies (involving mapping between items taken from disparate semantic domains), and within-domain analogies (involving mapping between items taken from proximal

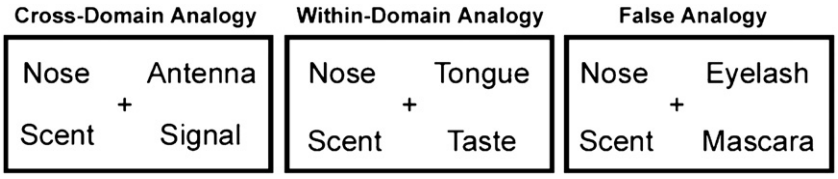

Fig. 1. Example stimuli (from Green et al., 2010). The figure displays examples of the 3 classes of trials presented to the participants in this study. The same word pair appeared on the left side in 1 trial of each class.

semantic domains; examples in Fig. 1; see Green et al., 2008 for discussion of the within-domain vs. cross-domain distinction in analogy). All stimuli were established as within-domain or cross-domain at a level of >90% agreement among the group of 84 independent raters; see Green et al. (2010). Equal numbers of within-domain and cross-domain analogy stimuli were used in creativity-cue and non-cue trials. All stimuli were determined *True* or *False* at >90% agreement among the separate group of 84 participants. False analogies were included as a manipulation check (half within-domain, half cross-domain). In order to reduce stimulus-specific confounding, the same 'base' word-pair (e.g., [Kitten:Cat]) was used on the left side in one trial of each stimulus type. All words were singular nouns. Visuo-spatial properties were consistent across stimuli; see Green et al. (2010) for details.

3. Results

Overall accuracy was 93.21%, SE = .32. A 2(Domain: Cross-domain, Within-domain) × 2(Validity: True, False) × 2(Cue: Creativity cue, Non-cue) ANOVA revealed no main effect of Domain ($F<1$), or Cue ($F(39)=3.45$, $p=.07$, $\eta_p^2=.08$) on accuracy, a main effect of Validity ($F(39)=7.26$, $p=.01$, $\eta_p^2=.16$), a Domain × Cue interaction ($F(39)=11.68$, $p=.001$, $\eta_p^2=.23$), a Cue × Validity interaction ($F(39)=5.46$, $p=.02$, $\eta_p^2=.12$), no Validity × Domain interaction ($F<1$), and a three-way Domain × Validity × Cue interaction ($F(39)=18.3$, $p<.001$, $\eta_p^2=.32$). Consistent with our central hypothesis, direct comparisons revealed that accuracy was significantly greater for cross-domain (more creative) analogies on creativity cue trials (94.53%, SE = .56) than cross-domain analogies on non-cue trials (91.66%, SE = .59; $t(39)=3.50$, SE = .82, $p=.001$). Critically, this effect was driven by greater accuracy for true cross-domain analogies on creativity cue trials (95.15%, SE = .72) than true cross-domain analogies on non cue trials (89.33%, SE = .80; $t(39)=5.62$, SE = 1.04, $p<.001$). Also consistent with our hypothesis, accuracy was not significantly different for false cross-domain analogies on creativity cue trials (93.9%, SE = .78) vs. false cross-domain analogies on non-cue trials (94%, SE = .74; $t(39)=.101$, SE = .99, $p=.92$), or for any direct contrast between false trials. Response times (RTs) were longer for creativity cue trials (M = 5206, SE = 58 ms) than for non-cue trials (M = 4702, SE = 46 ms; $t(39)=4.88$, SE = 1.31, $p<.001$). RTs were also longer for cross-domain analogies (M = 5065, SE = 64 ms) than for within-domain analogies (M = 4843, SE = 43 ms; $t(39)=3.18$, SE = 1.05, $p=.003$). As in previous studies of analogy in our laboratory and elsewhere, RTs were longer for true trials (M = 5298, SE = 53) than for false trials (M = 4610, SE = 46; $t(39)=5.03$, SE = 1.11, $p<.001$). Response times were longer for true cross-domain analogies on creativity cue trials (M = 5571, SE = 74 ms) than for true cross-domain analogies on non-cue trials (M = 5388, SE = 55 ms; $t(39)=2.73$, SE = 1.11, $p=.009$).

4. Discussion

We found that an explicit cue to think creatively led to improved performance in mapping true, cross-domain (creative) analogies without decreasing accuracy in identifying false analogies. These findings indicate that, while deliberately trying to think more creatively, subjects were more effective in creative generation of potential valid mappings for cross-domain analogies. The data also indicate that the improved performance on true cross-domain analogies was not the result of a general criterion shift to a more lenient decision threshold (i.e., participants did not cease to meet the appropriateness criterion of creativity). This is the first demonstration to our knowledge of a creativity cue enhancing analogical reasoning. This study is also unique in showing a selective enhancement of creativity with an item-level instructional cue across a large number of trials and using an objective, quantifiable measure of creative performance. The data indicate the extent to which an explicit cue can lead to successful conscious augmentation of creative state over short durations within an individual.

4.1. Semantic distance and creative analogy

While semantic distance does not exhaustively characterize creativity, our findings have bearing on creativity research. In the context of analogical reasoning, semantic distance is commonly identified as a determinant of creativity (i.e., more semantically distant analogies are more creative; e.g., Costello & Keane, 2000; Green et al., 2010, 2012; Holyoak & Thagard, 1995), and LSA-derived semantic distance values were highly consistent with the classification of within-domain vs. cross-domain analogies for our set of stimuli. Creativity is difficult or likely impossible to operationalize as a unitary construct. In order to gain insights into creative cognition, it is useful to address more constrained – preferably quantifiable – constructs, such as semantic distance, that are related to creativity. Our study tested the effect of semantic distance, coupled with a cue to think creatively, on cognitive processing in a reasoning task. As such, the current research focused only on the creativity required to generate semantically distant analogical mappings, and does not by any means constitute an exhaustive study of creativity. To our knowledge, this is the first study to examine semantic distance as a factor in reasoning, other than two brain-imaging investigations of neural loci associated with processing semantic distance, which we have recently carried out (Green et al., 2010, 2012). Critically, these prior studies did not involve a creativity cue.

4.2. Generating creative analogical mappings

The paradigm employed here differs from several previously employed verbal creativity paradigms in which participants gave written responses to prompts (e.g. Amabile, 1996; Guilford, 1967; Torrance, 1966), and from non-verbal creativity paradigms that examine divergent free responses (e.g., Haylock, 1987). The participants in our task did not generate new analogies. Nonetheless, the analogy task used in this study involves a type of creativity that is important for reasoning. In particular, although the elements of the analogies were all explicitly available, the mappings that connected them were not. The participants had to generate these mappings in order to correctly judge the analogies as true or false. Thus, the creative output was not the terms of the analogy, but the connection (mapping) that integrates them in a useful way. Recall that the participants did not know whether any given trial was valid or invalid beforehand – and invalid trials were included as a manipulation check – so they could not simply assume that the four-word set represented a

valid analogy. Instead, it was necessary to attempt to generate mapping(s) for each four-word set. The high level of response accuracy indicates that the participants were carrying out the task as instructed (i.e., attempting to generate mappings for each of the four-word stimuli).

The hypothesis that the process of covertly generating mappings to evaluate analogies is similar to the process of overtly generating creative analogical solutions is supported by two recent brain-imaging studies in our laboratory (Green et al., 2010, 2012). The first of these studies (Green et al., 2010) employed a paradigm similar to the one used in the present study, requiring subjects to evaluate whether four-word sets were valid analogies. The second study (Green et al., 2012) required subjects to generate solutions to incomplete (open-ended) analogies. Results indicated that the process of covertly generating mappings and overtly generating solutions relied on a highly similar network of temporal and prefrontal brain regions. Most importantly, these two studies demonstrated that the same region of left frontopolar cortex was the area most responsive to increases in semantic distance for both evaluating analogies and overtly generating solutions. Frontopolar cortex has been identified by convergent findings in several studies of analogical reasoning as critical for analogical mapping (Bunge, Wendelken, Badre, & Wagner, 2005; Cho et al., 2009; Geake & Hansen, 2005; Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006; Green et al., 2010, 2012; Hampshire, Thompson, Duncan, & Owen, 2011; Volle, Gilbert, Benoit, & Burgess, 2010; Wendelken, Nakhabenko, Donohue, Carter, & Bunge, 2008). In addition, increasing semantic distance had similar effects on response time and accuracy for both evaluation and overt generation.

Generating creative connections (mappings) between existing items and concepts is a valuable form of creativity with strong real-world applicability to reasoning (Donnelly & McDaniel, 1993; Dunbar & Blanchette, 2001; Holyoak & Thagard, 1995). While creative art sometimes involves creating a new something that did not previously exist, creative reasoning in the sciences (and in the arts as well) quite often involves finding valuable connections between things that are already well known. Highly creative insights reveal non-obvious but structurally informative analogical mappings that had previously not been identified, despite all the necessary elements of information being available. The well-known Bohr model of atomic structure, sparked by seeing the analogy between the atom and the solar system, is an example of this creative analogical insight, as are many other important analogies that have been the foundation for scientific models (e.g., between the heart and a water pump, between gas particles and billiard balls). The framing of models as analogies leads to specific predictions that can be empirically tested (e.g., Are the forces that hold planets near the sun the same as those that hold electrons near the nucleus?). Thus, even where the models are ultimately revised or proven incomplete, the creative analogical mappings are extremely valuable for real-world scientific advancement because they help scientists frame, test, and communicate models. Across a range of disciplines, insights that generate creative mappings between available pieces of information are extremely valuable, from identifying analogies across cultures in comparative literature and sociology, to seeing hypothesis-generating similarities between diseases in epidemiology (typically across great semantic distance).

The type of creativity involved in the present analogical mapping task represents a strong example of task-appropriateness. As noted above, there is near consensus among creativity researchers that task-appropriateness, and not just divergence, is an important element of the definition of creativity. Divergent ideas are truly creative only if they fit relevant environmental or task-related constraints, making them usable in some way (see Mayer, 1999, for a review). In the analogical mapping task, participants must generate mappings that apply to the four words presented on screen, and are constrained by the first-order relations between the two words on each side of the analogy. Otherwise they cannot accurately judge whether the analogies are valid. Generating mappings in this task therefore meets the definitional requirement of task-appropriateness, necessary for useful creativity.

4.3. Implications of dynamic creativity

These initial findings will support further research into conscious, acute augmentation of creativity and, preliminarily, have some noteworthy implications for the state vs. trait distinction in creativity research. Our findings have preliminary bearing on strategies in education and elsewhere aimed at bolstering the highly valued skill of analogical reasoning (e.g., Donnelly & McDaniel, 1993; Gick & Holyoak, 1980, 1983). Our data indicate that an explicit cue to think creatively was able to effectively augment reasoning for semantically distant analogies. These findings indicate the hypothesis that students might show improved performance if they were cued to think creatively when attempting to assimilate a novel concept being taught through analogy. This hypothesis is especially intriguing in the context of an extensive literature that indicates analogical reasoning as a core process for learning and an important strategy for teaching (Blanchette & Dunbar, 2002; Chi, Feltovich, & Glaser, 1981; Chiu & Lin, 2005; Donnelly & McDaniel, 1993, 2000).

With respect to the present findings, it is important to note that the increase in accuracy for cross-domain analogies that was associated with the creativity cue was relatively small (91.66% to 94.53%). This is likely due, at least in part, to a ceiling effect caused by testing a cohort of highly gifted undergraduate students. Future research should evaluate the cueing procedure in other populations to determine whether it can yield greater effects.

4.4. Neural mechanisms

Our findings are also relevant to possible neural mechanisms of creativity. Demonstrating a novel paradigm for contrasting more creative vs. less creative thinking across time within an individual has the potential to facilitate further research into the neural mechanisms of creativity, especially in within-subject fMRI paradigms. Previous work (Green et al., 2006, 2010, 2012) has shown that semantic distance in analogies correlates parametrically with greater activation in frontopolar cortex during analogical mapping. If increasing frontopolar activity generally reflects increasing creativity in neural processing, we would predict that the creativity cue manipulation described in the present work is likely to lead to greater activation in frontopolar cortex during analogical

reasoning. Building on the present study, future work will help to test this hypothesis and to further elucidate the neural bases of creativity in prefrontal regions.

5. Conclusions

These findings indicate that the ability to generate analogical mappings between semantically distant items can be improved by an explicit cue to think creatively. This is a novel demonstration of improved performance on a reasoning task elicited by a creativity cue on an acute time scale. This finding is relevant for education in that a cue to think creatively could enhance students' abilities to learn concepts via analogies. In addition, as a within-subjects manipulation, the paradigm reported here will allow for new avenues of investigation into the cognitive and neural mechanisms recruited when a person makes an effort to think more creatively.

References

Abdullaev, Y. G., & Posner, M. I. (1997). Time course of activating brain areas in generating verbal associations. *Psychological Science*, *8*, 56–59.

Amabile, T. M. (1996). *Creativity in context: Update to the social psychology of creativity*. Boulder, CO: Westview.

Blanchette, I., & Dunbar, K. (2002). Representational change and analogy: How analogical inferences alter target representations. *Journal of Expermental Psychology: Learning Memory, and Cognition*, *28*, 672–685.

Bunge, S. A., Wendelken, C., Badre, D., & Wagner, A. D. (2005). Analogical reasoning and prefrontal cortex: Evidence for separable retrieval and integration mechanisms. *Cerebral Cortex*, *15*, 239–249.

Carlsson, I., Wendt, P. E., & Risberg, J. (2000). On the neurobiology of creativity. Differences in frontal activity between high and low creative subjects. *Neuropsychologia*, *38*, 873–885.

Chen, C., Kasof, J., Himsel, A., Dmitrieva, J., Dong, Q., & Xue, G. (2005). Effects of explicit instruction to "be creative" across domains and cultures. *Journal of Creative Behavior*, *39*, 89–110.

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, *5*, 121–152.

Chiu, M. -H., & Lin, J. -W. (2005). Promoting fourth graders' conceptual change of their understanding of electric current via multiple analogies. *Journal of Research in Science Teaching*, *42*, 429–464.

Cho, S., Moody, T. D., Fernandino, L., Mumford, J. A., Poldrack, R. A., et al. (2009). Common and dissociable prefrontal loci associated with component mechanisms of analogical reasoning. *Cerebral Cortex*, *20*, 524–533.

Costello, F. J., & Keane, M. T. (2000). Efficient creativity: Constraint-guided conceptual combination. *Cognitive Science*, *24*, 299–349.

Dahl, D. W., & Moreau, P. (2002). The influence and value of analogical thinking during new product ideation. *Journal of Marketing Research*, *39*, 47–60.

Dai, D. Y., & Renzulli, J. S. (2008). Snowflakes, living systems, and the mystery of giftedness. *Gifted Child Quarterly*, *52*, 114–130.

Donnelly, C. M., & McDaniel, M. A. (1993). Use of analogy in learning scientific concepts. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*, 975–987.

Donnelly, C. M., & McDaniel, M. A. (2000). Analogy with knowledgeable learners: When analogy confers benefits and exacts costs. *Psychonomic Bulletin and Review*, *7*, 537–543.

Dunbar, K., & Blanchette, I. (2001). The in vivo/in vitro approach to cognition: The case of analogy. *Trends in Cognitive Science*, *5*, 334–339.

Geake, J. G., & Hansen, P. C. (2005). Neural correlates of intelligence as revealed by fMRI of fluid analogies. *Neuroimage*, *26*, 555–564.

Gick, M. L., & Holyoak, K. J. (1980). Analogical problem solving. *Cognitive Psychology*, *12*, 306–355.

Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology*, *15*, 1–38.

Gilchrist, M. B., & Taft, R. (1972). Originality on demand. *Psychological Reports*, *31*, 579–582.

Green, A. E., Fugelsang, J. A., Kraemer, D. J. M., & Dunbar, K. N. (2008). The micro-category account of analogy. *Cognition*, *106*, 1004–1016.

Green, A. E., Fugelsang, J. A., Kraemer, D. J. M., Gray, J. R., & Dunbar, K. N. (2010). Connecting long distance: Semantic distance in analogical reasoning modulates frontopolar cortex activity. *Cerebral Cortex*, *20*, 70–76.

Green, A. E., Fugelsang, J. A., Kraemer, D. J. M., Gray, J. R., & Dunbar, K. N. (2012). Neural correlates of creativity in analogical reasoning. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *38*, 264–272.

Green, A. E., Fugelsang, J. A., Kraemer, D. J. M., Shamosh, N. A., & Dunbar, K. N. (2006). Frontopolar cortex mediates abstract integration in analogy. *Brain Research*, *1096*, 125–137.

Guilford, J. P. (1950). Creativity. *American Psychologist*, *5*, 444–454.

Guilford, J. P. (1967). *The nature of human intelligence*. New York: McGraw-Hill.

Hampshire, A., Thompson, R., Duncan, J., & Owen, A. M. (2011). Lateral prefrontal cortex subregions make dissociable contributions during fluid reasoning. *Cerebral Cortex*, *21*, 1–10.

Harrington, D. M. (1975). Effects of explicit instructions to "be creative" on the psychological meaning of divergent thinking test scores. *Journal of Personality*, *43*, 434–454.

Haylock, D. W. (1987). Mathematical creativity in schoolchildren. *Journal of Creative Behavior*, *21*, 48–59.

Holyoak, K. J., & Thagard, P. (1995). *Mental leaps*. Cambridge (MA): MIT Press.

Howard-Jones, P. A., Blakemore, S. J., Samuel, E. A., Summers, I. R., & Claxton, G. (2005). Semantic divergence and creative story generation: An fMRI investigation. *Cognitive Brain Research*, *25*, 240–250.

Landauer, T. K., & Dumais, S. (1997). A solution to Plato's problem: The latent semantic analysis theory of acquisition, induction and representation of knowledge. *Psychological Review*, *104*, 211–240.

Landauer, T. K., Foltz, P. W., & Laham, D. (1998). Introduction to latent semantic analysis. *Discourse Processes*, *25*, 259–284.

Mayer, R. E. (1999). Fifty years of creativity research. In R. J. Sternberg (Ed.), *Handbook of creativity* (pp. 449–460). Cambridge (UK): Cambridge University Press.

O'Hara, L. A., & Sternberg, R. J. (2001). It doesn't hurt to ask: Effects of instructions to be creative, practical, or analytical on essay-writing performance and their interaction with students' thinking styles. *Creativity Research Journal*, *13*, 197–210.

Pirkko, L. (1975). Increasing creativity through art education among preschool children. *Studies in Education, Psychology, & Social Research*, *29*, 44.

Raven, J., Raven, J. C., & Court, J. H. (1998). *Manual for Raven's progressive matrices and vocabulary scales, section 3: The standard progressive matrices*. San Antonio, TX: The Psychological Corporation.

Roid, G. H. (2003). *Stanford–Binet intelligence scales* (Fifth edition). Itasca, IL: Riverside Publishing.

Rose, L. H., & Lin, H. -T. (1984). A meta-analysis of long-term creativity training programs. *The Journal of Creative Behavior*, *18*, 11–22.

Schunn, C. D., Paulus, P. B., Cagan, J., & Wood, K. (2006). *Final report from the NSF innovation and discovery workshop: The scientific basis of individual and team innovation and discovery*. Washington (DC): National Science Foundation.

Scott, G., Leritz, L. E., & Mumford, M. D. (2004). The effectiveness of creativity training: A quantitative review. *Creativity Research Journal*, *16*, 361–388.

Seger, C. A., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. E. (2000). Functional magnetic resonance imaging evidence for right-hemisphere involvement in processing unusual semantic relationships. *Neuropsychology*, *14*, 361–369.

Sternberg, R. J. (1997). *Successful intelligence*. New York: Plume.

Torrance, E. P. (1966). *Torrance tests of creative thinking*. Princeton, N.J.: Personnel Press.

Volle, E., Gilbert, S. J., Benoit, R. G., & Burgess, P. W. (2010). Specialization of the rostral prefrontal cortex for distinct analogy processes. *Cerebral Cortex*, *20*, 2647–2659.

Wechsler, D. (1997). *WAIS-III administration and scoring manual*. San Antonio, TX: The Psychological Corporation.

Wendelken, C., Nakhabenko, D., Donohue, S. E., Carter, C. S., & Bunge, S. A. (2008). "Brain is to thought as stomach is to ??": Investigating the role of rostrolateral prefrontal cortex in relational reasoning. *Journal of Cognitive Neuroscience*, *20*, 682–693.

Woodcock, R. W., McGrew, K. S., & Mather, N. (2001). *Woodcock–Johnson III tests of cognitive abilities*. Itasca, IL: Riverside Publishing.