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Far-Out Thinking: Generating Solutions to Distant Analogies Promotes Relational Thinking

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Abstract
Is it possible to induce a mind-set that will affect relational thinking in a subsequent reasoning task involving unrelated materials? We investigated whether evaluating the validity of verbal analogies (Experiment 1a) or generating solutions for them (Experiment 1b) could induce a relational mind-set that would transfer to an unrelated picture-mapping task. The verbal analogies were based on either near or far semantic relations. We found that generating (but not evaluating) solutions for semantically distant analogies increased the proportion of relational mappings on the transfer task, even after we controlled for fluid intelligence and response time. Solving near analogies did not produce transfer. Generation of solutions to far analogies appears to provide a potent method for triggering a mind-set that can enhance relational thinking in a different task.

Keywords
analogical reasoning, relational transfer, semantic distance, creativity

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> To create consists precisely in not making useless combinations and in making those which are useful . . . . Among chosen combinations the most fertile will often be those formed of elements drawn from domains which are far apart. (Poincaré, 1913, p. 386)

As Poincaré recognized over a century ago, creative innovations often involve nonrandom combinations of ideas drawn from disparate domains. A creative product is not only novel but also useful, in that it satisfies task constraints (Kaufman & Sternberg, 2007). The psychological and neural mechanisms underlying creativity are only beginning to be understood (for reviews, see Smith & Ward, 2012; Van Steenburgh, Fleck, Beeman, & Kounios, 2012). One basic mechanism for identifying constrained correspondences between semantically distant domains is analogical reasoning (Gentner, 1983; Gick & Holyoak, 1980). Analogy has been shown to be effective in guiding creative thinking and innovation in science, education, and industry (e.g., Chan, Paletz, & Schunn, 2012; Costello & Keane, 2000; Dahl & Moreau, 2002; Dunbar & Blanchette, 2001; Holyoak & Thagard, 1995; Schunn, Paulus, Cagan, & Wood, 2006).

Behavioral, neural, and computational studies suggest close links between cross-domain analogical reasoning and abstract thinking (Christoff & Keramatian, 2007; Gick & Holyoak, 1983; Knowlton, Morrison, Hummel, & Holyoak, 2012). Similar brain areas, most notably the rostrolateral prefrontal cortex, are selectively activated by tasks involving complex nonverbal reasoning (Cho et al., 2010; Christoff et al., 2001), four-term verbal analogy problems based on semantically distant domains (Bunge, Wendelken, Badre, & Wagner, 2005; Green, Fugelsang, Kraemer, Gray, & Dunbar, 2010), and a mind-set to expect an abstract problem while solving anagrams (Christoff, Keramatian, Gordon, Smith, & Mädler, 2009).

Analogical reasoning is closely connected not only to creativity but also to individual differences in IQ, particularly the component of fluid intelligence (Snow, Kyllonen, & Marshalek, 1984). Although IQ and creativity can be dissociated as separate traits (Herr, Moore, & Hansen,

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1965; Hocevar, 1980; Kim, 2005), analogical reasoning appears to bridge them (Holyoak, 2012). In particular, it has been proposed that cross-domain analogies tap into creative processing (Barnett & Ceci, 2002; Bowdle & Gentner, 2005; Holyoak & Thagard, 1995). The role of semantic distance has been explored in particular detail for four-term verbal analogy problems. Such problems consist of two pairs of terms; the participant must find the relation between the items in each pair and then determine whether the relations match across the two pairs. Relative to problems based on near semantic relations (e.g., *furnace:coal::woodstove:wood*), those based on semantically distant relations (e.g., *furnace:coal::stomach:food*) are rated as more creative and show a greater benefit when reasoners are cued to "think more creatively" (Green, Cohen, Kim, & Gray, 2012, p. 600). Whereas near analogies can be solved by matching identical relations (e.g., the furnace burns coal as a woodstove burns wood), distant analogies require evaluating or generating a more abstract relation that bridges the domains (e.g., the furnace burns coal as the stomach "burns" food). As semantic distance increases, both the evaluation of analogical validity (Green et al., 2010) and the generation of a missing term to complete the analogy (Green, Fugelsang, Kraemer, Gray, & Dunbar, 2012) reveal a parametric increase in activation of the rostrolateral prefrontal cortex.

There is thus strong evidence that solving certain types of specific problems evokes abstract relational reasoning. In the present study, we addressed a less specific question: Can a more general "mind-set" induced by solving cross-domain verbal analogy problems promote relational reasoning in a different task using unrelated materials? The task used to induce a more general mind-set was based on the verbal analogies used previously by Green et al. (2010, 2012; see also Vendetti, Knowlton, & Holyoak, 2012). The transfer task involved finding correspondences between objects in two visual scenes (task and scenes adapted from Markman & Gentner, 1993). For each pair of scenes, two plausible options were available: a featural match (i.e., two objects sharing salient visual and semantic similarities) and a relational match (i.e., two featurally dissimilar objects that play similar relational roles in their respective scenes). We hypothesized that if the verbal analogy task promotes more abstract thinking, then relational matches would be favored over featural matches in the subsequent picture-mapping task.

The main manipulation was whether the verbal task involved semantically near or far analogies. On the basis of previous work, we expected far analogies to elicit more creative processing than would near analogies (Chan et al., 2011; Green, Fugelsang, et al., 2012). Across two experiments, we also varied the nature of the verbal analogy task. In Experiment 1a, participants decided whether a four-term analogy problem (e.g., *furnace:coal::stomach:food*) was valid or invalid (i.e., whether the semantic relationship between the terms in each pair was similar or dissimilar, respectively); in Experiment 1b, participants were asked to generate a valid completion for an incomplete analogy (e.g., *furnace:coal::stomach:?*). Although both tasks may elicit greater creativity when the problems are based on far rather than near analogies, theories of creative cognition imply that the generation task would be especially effective in eliciting a mind-set that would transfer to different relations (Ellamil, Dobson, Beeman, & Christoff, 2012; Finke, Ward, & Smith, 1992). Novel and useful ideas are hypothesized to arise from an interplay of generative processes that produce candidate ideas and from exploratory processes that expand on those ideas and evaluate them. To generate a solution to a far-analogy problem in the *A:B::C:D* format when the *D* term is left blank, the reasoner must retrieve potential options based on semantic relations (e.g., concepts related to the *C* term or higher-order relations that link the *A:B* relation to potential relations based on *C*). The correct *D* option must then be selected by evaluating the joint constraints provided by the *A:B* relation and the *C* term. In contrast, evaluating a complete analogy problem (i.e., when the *D* term is stated) bypasses the need for generation of a term to complete the analogical structure and, therefore, would be expected to be less effective in inducing a mind-set that could transfer to novel materials.

General Method

The designs of Experiments 1a and 1b were identical. Participants solved four-term verbal analogy problems, with half of the participants receiving near analogies and half receiving far ones. Immediately afterward, all participants completed a picture-mapping task based on unrelated materials.

The stimuli for the four-term verbal analogy task were modified versions of those used by Green et al. (2010). There were a total of 120 analogy problems, each consisting of four words in an *A:B::C:D* format. Problems were divided into four types: valid near (40 problems), valid far (40), invalid near (20), and invalid far (20). Near trials were those for which the *C:D* concepts were drawn from a category semantically similar to that of the *A:B* pair. For example, for the *A:B* pair *nose:scent*, the near *C:D* pair was *tongue:taste*, whereas the far *C:D* pair was *antenna:signal*. Valid trials were those for which the *A:B* relationship was the same as or highly similar to that for the *C:D* pair (e.g., "sense organ for" in the example of a near analogy such as *nose:scent::tongue:taste*) or could be generalized into a more abstract relation that also fit the *C:D* pair (e.g., "detects a type of signal" for the example of a far analogy such as *nose:scent::antenna:signal*). (For more detailed information about the stimuli, see Green et al., 2010.)

The transfer task involved picture mapping and used materials adapted from Markman and Gentner (1993), with additional items added by Tohill and Holyoak (2000). In this task (see Fig. 1), participants were shown two scenes at the same time. After 10 s, one of the objects in the top scene was highlighted. In the example shown in Figure 1, this was the umbrella. Participants were then asked to choose the object in the bottom scene that "goes with" the highlighted object in the top scene. For each pair of scenes, the bottom picture included both a potential featural match (e.g., the umbrella over the coffee stand) and a potential relational match (e.g., the newspaper the woman is holding over her head). The "goes with" instruction was intentionally left vague so that participants might reasonably choose either the featural or the relational match.

Participants were tested individually. After reading the instructions, participants received three analogy practice trials with feedback from the experimenter. Using a between-subjects design, we randomly assigned each participant to solve either near or far analogies. Each participant solved 60 problems (40 valid, 20 invalid). There were 10 pairs of scenes, and the order of trial presentation was randomized across participants. Experiments were conducted on a desktop computer, and all the stimuli were presented on a CRT monitor. Stimuli were generated and data were collected using Superlab Software (Cedrus Corporation, 2004). All experimental procedures were approved by the Committee for Protection of Human Subjects at UCLA.

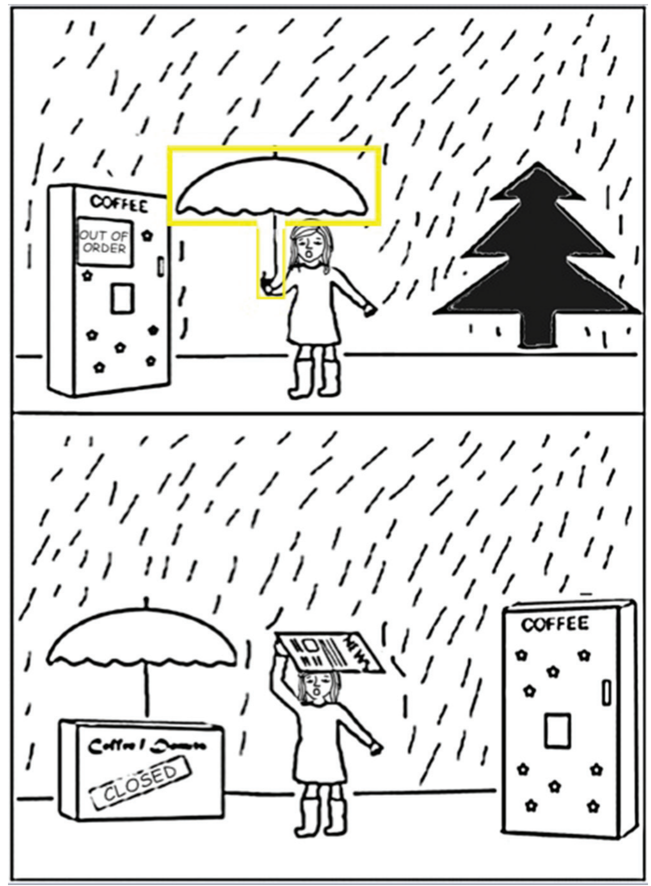

Fig. 1. Example of a pair of scenes used in the picture-mapping task (adapted from Markman & Gentner, 1993, and Tohill & Holyoak, 2000). Participants were shown both scenes at the same time. After 10 s, one of the objects in the top scene was highlighted (here, the umbrella), and participants had to indicate which object in the bottom scene "goes with" the highlighted object in the top scene. For each pair of scenes, the bottom picture included both a potential featural match (here, the umbrella over the coffee stand) and a potential relational match (here, the newspaper the woman is holding over her head, which performs a function similar to the umbrella's in the top scene).

Method

Experiment 1a

Participants. Seventy-seven undergraduate participants were recruited through the Psychology Department participant pool at the University of California, Los Angeles (UCLA). The participants ranged in age from 18 to 21 years (M = 20.1, SD = 1.2). All were fluent in English and received course credit for their participation.

Procedure. Each trial began with a 500-ms fixation cross, followed by presentation of the *A:B* and *C:D* pairs. The *A:B* pair appeared on the computer monitor above the *C:D* pair. Participants were instructed to press a key with their right index finger if the analogy was valid and to hit a different key with the left index finger if the analogy was invalid. They were told to solve each trial as quickly and accurately as possible. Feedback was provided if the participant made the wrong decision or if 8 s elapsed before a decision was made. If the participant's choice was wrong, the screen displayed "Wrong!"; if the participant took too long, the screen displayed "Too Slow!" Both types of feedback were shown centered in red font for 1 s, after which the next trial began. The picture-mapping task was then administered. Experiment 1a lasted approximately 30 min.

Experiment 1b

Participants. Fifty-four undergraduate participants were recruited through the UCLA Psychology Department participant pool. The participants ranged in age from 18 to 22 years (M = 20.7, SD = 1.3). All were fluent in English and received course credit in return for their participation.

Procedure. In Experiment 1b, participants first completed an abridged version of Raven's Advanced Progressive Matrices (RAPM; Arthur, Tubre, Paul, & Sanchez-Ku, 1999). This test provides a measure of fluid intelligence, allowing us to assess potential individual differences in analogy performance.

After solving RAPM, each participant completed the verbal analogy task using the same basic stimuli as in Experiment 1a. However, only the valid-analogy problems were presented. Each problem was shown with the *D* term missing, and participants were prompted to type in an appropriate response to complete the analogy problem. There was no time limit in which participants had to answer, and no feedback was given. The picture-mapping task was then administered. Experiment 1b lasted approximately 45 min.

Results

Experiment 1a

As measured by the proportion of correct responses, participants in the far-analogy group were significantly less accurate in evaluating analogies (M = .79, SD = .13) than those in the near-analogy group (M = .86, SD = .09), $t(75)$ = 2.66, p < .01, η_p^2 = .03. Participants in the far-analogy group also took significantly longer to accept valid analogies (M = 3,226 ms, SD = 720) than did participants in the near-analogy group (M = 2,689 ms, SD = 500), $t(75)$ = 3.78, p < .001, η_p^2 = .05. These findings replicate those of previous studies using the same verbal analogy problems (Green et al., 2010; Vendetti et al., 2012).

As shown in Figure 2, no transfer effect was found in the picture-mapping task, as the proportion of relational responses did not differ significantly after solving far verbal analogies (M = .48, SD = .29) than after solving near verbal analogies (M = .53, SD = .31), $t(75)$ = 0.57, p > .57.

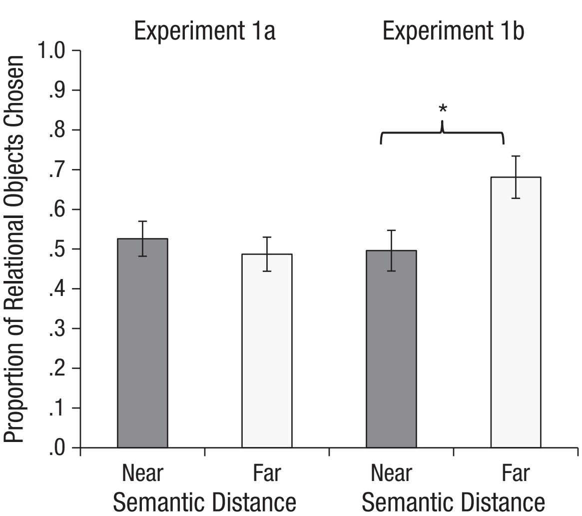

Fig. 2. Results from Experiment 1a and Experiment 1b: mean proportion of relational objects chosen in the picture-mapping task as a function of the semantic distance between word pairs in the verbal analogy task. The asterisk indicates a significant difference between conditions (*p < .01). Error bars denote standard errors of the mean.

Experiment 1b

Participants in the near-analogy group were more accurate (as measured by the proportion of correct responses) in generating solutions to verbal analogy problems (M = .85, SD = .07) than participants in the far-analogy group were (M = .56, SD = .13), $t(52)$ = 7.69, p < .001, η_p^2 = 12.9. These results replicate the finding of Green, Fugelsang, et al. (2012).

In evaluating potential transfer to relational thinking in the picture-mapping task, we included several covariates: fluid-intelligence score (based on performance on RAPM), accuracy score, and mean solution time in the verbal analogy task. As Figure 2 shows, participants who generated solutions for far-analogy problems gave a significantly greater proportion of relational responses on the picture-mapping task (M = .68, SD = .19) than did participants who generated solutions for the near-analogy problems (M = .49, SD = .23), $F(1, 49)$ = 8.48, MSE = 0.04, p < .005, η_p^2 = .15.

To provide a more direct comparison of transfer effects after evaluation (Experiment 1a) versus solution generation (Experiment 1b) of verbal analogy problems, we performed an additional analysis of variance including the two experiments as a between-subjects factor, with the proportion of relational responses in the picture-mapping task as the dependent variable. A significant interaction was obtained, $F(1, 127)$ = 5.44, MSE = 0.07, p < .02, η_p^2 = .04, which indicates that the transfer effect produced by solving far analogies was specific to the generation task (Experiment 1b).

We also performed correlational analyses to examine the impact of fluid intelligence on relational thinking in the picture-mapping task in Experiment 1b. Overall, there was a trend for a positive relationship between fluid intelligence and the proportion of relational responses during the picture-mapping task, $r(52)$ = .24, p = .08. When the correlation between fluid intelligence and relational responses was examined separately for each semantic-distance group, a significant positive correlation was found for those who generated solutions to near-analogy problems, $r(26)$ = .41, p < .03, but not for those who generated solutions to far-analogy problems, $r(24)$ = .09, p > .64.

General Discussion

We found evidence that solving cross-domain verbal analogy problems can promote relational reasoning in a different task using unrelated materials. The evocation of this general "mind-set" by cross-domain analogies was limited to when participants had to generate solutions, a finding consistent with cognitive theories of creativity focusing on generation as an especially important process involved in creativity (Ellamil et al., 2012; Finke et al., 1992). Simply evaluating analogies largely eliminates the need to complete the analogical structure.

The impact of the relational mind-set induced by generating solutions for far analogies was observed even when we controlled for fluid intelligence, overall accuracy, and response time in the verbal analogy task. Our findings support previous research demonstrating a dissociation between IQ and creativity (Herr et al., 1965; Hocevar, 1980; Kim, 2005). At the same time, fluid intelligence is also closely linked to analogical reasoning. For the condition in Experiment 1b that did not evoke a transfer-promoting mind-set (generating solutions to near analogies), the proportion of relational responses produced in the picture-mapping task was predicted by performance on RAPM, a measure of fluid intelligence. By contrast, fluid intelligence did not predict relational responding in the picture-mapping task after a facilitatory mind-set had been triggered by generating solutions to far verbal analogies. Moreover, because participants in both conditions of Experiment 1b completed RAPM at the beginning of the experimental session, we can rule out the possibility that any complex relational task (e.g., the more difficult problems on RAPM itself) is sufficient to evoke a mind-set that transfers to the picture-mapping task. These findings suggest that fluid intelligence and creativity are distinct factors influencing relational processing, in which a mind-set overrides individual differences in fluid intelligence (at least within the relatively high intelligence range of our college-student population). The overlap in neural-activation patterns associated with complex analogical reasoning (Bunge et al., 2005; Cho et al., 2010), creativity (Ellamil et al., 2012; Green, Fugelsang, et al., 2012), and abstract thought (Christoff et al., 2009) support the hypothesis that multiple manifestations of relational processing are dependent on the rostrolateral prefrontal cortex.

Given that we were able to induce relational thinking in a different task using unrelated materials, future research could investigate how this type of mind-set induction affects other tasks that should benefit from creativity. Previous findings using the in vivo approach within both scientific fields (Dunbar & Blanchette, 2001) and industry (Chan et al., 2012; Dahl & Moreau, 2002; Wilson, Rosen, Nelson, & Yen, 2010) suggest that using cross-domain analogies, compared with staying within a superficially similar domain, is more likely to lead to creative and innovative outcomes when generating ideas. Our research supports this possibility, which is consistent with other research exploring transfer effects related to problem solving and abstract thought (Chrysikou, 2006; McCaffrey, 2012). The present results provide the first experimental demonstration that having people generate solutions for semantically distant analogies induces a mind-set that influences a different relational-reasoning task using unrelated materials.

Author Contributions

M. S. Vendetti and K. J. Holyoak developed the study concept. All authors contributed to the study design. Testing and data collection were performed by A. Wu. A. Wu and M. S. Vendetti interpreted and analyzed the data under the supervision of K. J. Holyoak. M. S. Vendetti drafted the manuscript, and K. J. Holyoak provided critical revisions. All authors approved the final version of the manuscript for submission.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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