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Neural Correlates of Creativity in Analogical Reasoning

Adam E. Green
Georgetown University

David J. M. Kraemer
University of Pennsylvania

Jonathan A. Fugelsang
University of Waterloo

Jeremy R. Gray
Yale University

Kevin N. Dunbar
University of Maryland

Brain-based evidence has implicated the frontal pole of the brain as important for analogical mapping. Separately, cognitive research has identified semantic distance as a key determinant of the creativity of analogical mapping (i.e., more distant analogies are generally more creative). Here, we used functional magnetic resonance imaging to assess brain activity during an analogy generation task in which we varied the semantic distance of analogical mapping (as derived quantitatively from a latent semantic analysis). Data indicated that activity within an a priori region of interest in left frontopolar cortex covaried parametrically with increasing semantic distance, even after removing effects of task difficulty. Results implicate increased recruitment of frontopolar cortex as a mechanism for integrating semantically distant information to generate solutions in creative analogical reasoning.

Keywords: analogical reasoning, frontopolar, creativity, fMRI, mapping

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Analogical reasoning has been widely identified as a cognitive process that is important for creativity (Barnett & Ceci, 2002; Boden, 2003; Bowdle & Gentner, 2005; Costello & Keane, 2000; Green, Fugelsang, Kraemer, & Dunbar, 2008; Green, Kraemer, Fuselsang, Gray, & Dunbar, 2010; Holyoak & Thagard, 1995; Mayer, 1999; Sternberg, 1977). The nature of the link between analogy and creativity can be discerned in a definition of creativity that has gathered virtual consensus among creativity researchers (Mayer, 1999): Creativity is novel generation fitted to the constraints of a particular task. This definition contains two key characteristics, novelty and constraint, which frequently describe analogical reasoning. Analogical reasoning (e.g., *blizzard* is to *snowflake* as *army* is to ?) centers on analogical mappings, which can constitute novel connections between situations or representations that do not seem similar on the surface (e.g., the mapping between the relational representations [blizzard : snowflake] and [army : soldier]). In addition, analogical reasoning must fit particular constraints. As an example, attempting a mapping between [blizzard : snowflake] and [army : war] may be novel, but it does not succeed as an analogy because it does not adequately fit the constraints of analogical reasoning (Gentner, 1983; Holyoak & Thagard, 1989; Weitzenfeld, 1984).[1] The connection between analogy and creativity is also supported by plentiful real-world examples of creative advancements based on analogical insights, as when August Kekulé mapped the carbon–carbon bonds of the benzene ring after having a daydream in which a snake bit its own tail, or when James Crocker mapped from the extendable shower head in his hotel room the position control mechanism for the mirrors on the Hubble telescope.

The relationship between analogy and creativity is not general or universal: Some analogies are more creative than others, and some are not very creative at all. A key determinant of creativity

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Adam E. Green, Department of Psychology, Georgetown University; David J. M. Kraemer, Department of Psychology, University of Pennsylvania; Jonathan A. Fugelsang, Department of Psychology, University of Waterloo, Waterloo, Ontario, Canada; Jeremy R. Gray, Department of Psychology, Yale University; Kevin N. Dunbar, Department of Psychology, University of Maryland.

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Correspondence concerning this article should be addressed to Adam E. Green, Department of Psychology, Georgetown University, 302C White-Gravenor Hall, 3700 O Street, NW, Box 571001, Washington, DC 20057. E-mail: aeg58@georgetown.edu

[1] In this case, a pertinent constraint is that the words within the second relation [army : ?] must not only be related to each other but must be related to each other in a way that is similar to the way in which the words in the first relation [blizzard : snowflake] are related.

in analogy is the extent to which the items being mapped are relatively close or relatively distant with respect to their superficial semantic features (Barnett & Ceci, 2002; Boden, 2003; Bowdle & Gentner, 2005; Green et al., 2008, Green et al., 2010; Holyoak & Thagard, 1995). The semantic distance between items being mapped is related to the novelty component of creativity, because more distant mappings are generally less obvious and so they tend to be more novel—this also frequently makes them more valuable (Dunbar & Blanchette, 2001; Holyoak & Thagard, 1995; Sternberg, 1997). Nonetheless, these mappings must fit the constraints of analogical reasoning to produce valid analogies (Bowdle & Gentner, 2005; Costello & Keane, 2000; Green et al., 2010; Holyoak & Thagard, 1995). Although creative analogies represent deep-lying similarities between relational representations that are superficially dissimilar, as in a mapping between [kitten : cat] and the superficially dissimilar [spark : fire], analogies that are relatively less creative are often mapped between relational representations that are superficially quite similar, as in a mapping between [kitten : cat] and [puppy : dog]. The fact that analogies vary with respect to the semantic distance between items being mapped and the fact that this variation is related to creativity in analogy combine to represent an empirical opportunity to investigate the quantifiable parameter of semantic distance as a window into creativity in analogical reasoning. Verbal four-term analogies are readily adapted as stimuli for neurocognitive testing because their relatively simple form allows experimental control of stimulus properties, and these analogies are well suited to represent semantic distance.

Despite the generally recognized importance of creative analogical reasoning as a tool for revealing insightful connections and generating innovative ideas in the sciences, as well as in arts and industry (Boden, 2003; Dahl & Moreau, 2002; Dunbar & Blanchette, 2001; Holyoak & Thagard, 1995), brain-imaging studies of analogical reasoning have yet to examine parameters directly related to creativity. Likewise, studies of creative thinking have typically been constructed without the constraints of a reasoning task, focusing instead on the novelty component of creativity (Carlsson, Wendt, & Risberg, 2000; Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005). Thus, key unresolved questions remain concerning the neural processes that support integration of semantically distant concepts in service of creative analogical reasoning.

Here, we undertook a brain-imaging study of semantic distance in generating analogical solutions. Brain-imaging studies have implicated the frontal pole of the brain in complex cognition related to analogical reasoning (Bunge, Wendelken, Badre, & Wagner, 2005; Cho et al., 2009; Geake & Hansen, 2005; Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006; Green et al., 2010; Hampshire, Thompson, Duncan, & Owen, 2011; Volle, Gilbert, Benoit, & Burgess, 2010; Wendelken, Nakhabenko, Donohue, Carter, & Bunge, 2008). In particular, a circumscribed region within left frontopolar cortex is specifically involved in the mapping component of analogical reasoning (Green, Fugelsang, Kraemer, et al., 2006; Green et al., 2010). Although analogical reasoning involves several component processes in addition to mapping, a well-developed analogy literature has identified mapping as the component of analogical reasoning in which semantic distance is bridged during creative analogical reasoning (Barnett & Ceci, 2002; Bowdle & Gentner, 2005; Holyoak & Thagard, 1995). This is because mapping is the component of analogy in which connections are formed between similar elements in seemingly disparate representations (Green, Fugelsang, & Dunbar, 2006; Green et al., 2008, Green et al., 2010; Holyoak & Thagard, 1995).

We have recently found that when participants evaluated analogies as true or false, activity in frontopolar cortex increased as the semantic distance in the analogies increased (Green et al., 2010). This finding extended previous evidence that frontopolar cortex plays a key role in analogical mapping (Bunge et al., 2005; Geake & Hansen, 2005; Green, Fugelsang, Kraemer, et al., 2006) and that analogical mapping is critical for integrating semantically distant representations (Costello & Keane, 2000; Holyoak & Thagard, 1995; Sternberg, 1977). This finding leads to the further hypothesis that activity in frontopolar cortex underlies not only evaluation of creative analogies but also the generation of creative analogical solutions across semantic distance. Here, we tested and found support for this hypothesis within an a priori predicted region of interest (ROI) in frontopolar cortex. We varied the semantic distance values, as derived quantitatively from a latent semantic analysis (Landauer, Foltz, & Laham, 1998) of verbal analogy stimuli that had the form "*A* is to *B* as *C* is to ?" Parametric analyses revealed that semantic distance predicted activity in the frontopolar ROI during analogical reasoning, even after statistically removing the effect of task difficulty. Moreover, independent ratings of our stimuli confirmed that more semantically distant analogies were judged to be more creative. Our findings thus provide a first brain-based characterization of creative generation in analogical reasoning, identifying increasing frontopolar recruitment as a key mechanism.

Method

Participants

Twenty-three right-handed native English speakers (12 men, mean age = 22.2 years) were recruited from the local college community to participate in the functional magnetic resonance imaging (fMRI) study. Informed written consent for all participants was obtained prior to the experiment in accordance with the guidelines established by the Committee for the Protection of Human Subjects at Dartmouth College. A separate group of 84 undergraduate native English speakers (18 men, mean age = 21.8 years) rated the stimuli. Informed written consent for all participants was obtained prior to the experiment in accordance with the guidelines established by the Human Research Ethics Committee at the University of Waterloo.

Stimuli and Procedure

Participants completed 80 analogy trials during four event-related fMRI runs. On each trial, participants viewed an analogy problem comprising three words and a question mark (see Figure 1) and covertly generated a solution word to complete the analogy. They immediately pressed a button to indicate they had generated a solution. A correct solution word then appeared onscreen in place of the question mark, and participants indicated whether the word they generated was the same or very similar to the word that appeared.

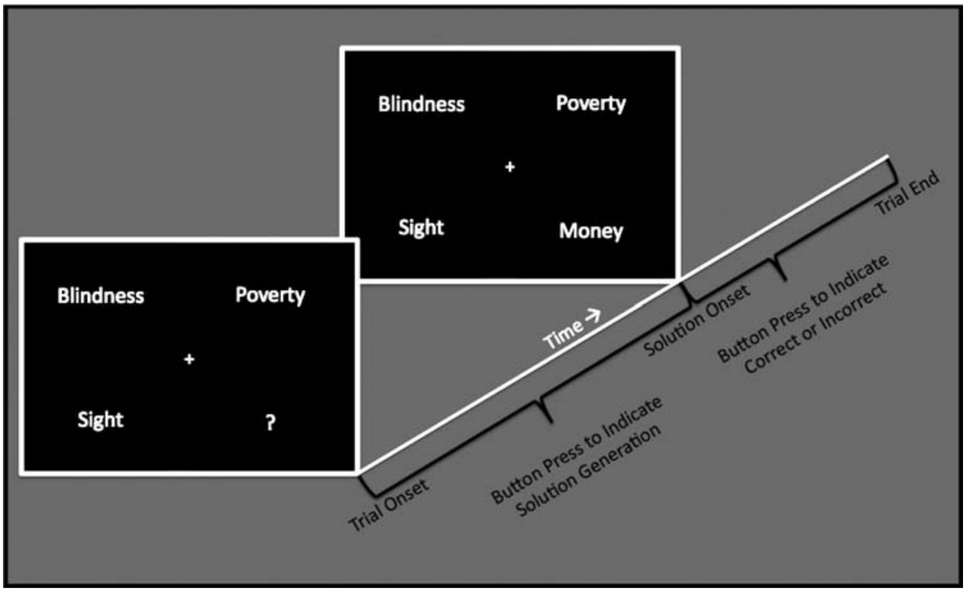

Figure 1. Generation task. The figure displays an example analogy trial presented to participants during functional magnetic resonance imaging.

The semantic distance value for each analogy item was obtained using latent semantic analysis. In particular, semantic distance values were calculated between the word pairs constituting the left and right halves of each complete analogy. The latent semantic analysis application (available from 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. Semantic distance values were used in the main parametric analysis. Specifically, these values allowed us to identify regions of the brain where semantic distance correlated with stimulus-related activity in a parametric relationship. In addition, 84 independent raters used a 7-point scale to rate all analogy stimuli for creativity ("How much creativity does generating this solution demand?" with the endpoints of the creativity rating scale being 1 = *least creativity* and 7 = *most creativity*). These raters also rated each item for difficulty ("How difficult is it to generate a solution for this analogy?" with endpoints 1 = *least difficult* and 7 = *most difficult*). We used these ratings as a parametric regressor for subsequent fMRI analysis and to test predictions regarding the relatedness of these parameters with respect to analogical mapping. In particular, we predicted that creativity ratings would track with semantic distance values for the analogy items (i.e., the more semantically distant the two halves of the analogy, the more creative their analogical connection). Consistent with our prediction, semantic distance values were highly correlated with mean ratings for creativity ($r = .92$, $p < .001$). Semantic distance values were also correlated with rated difficulty ($r = .39$, $p = .001$).

To reduce stimulus-specific confounding, we used the same base word pair (e.g., [blindness : sight]) on the left side in two analogy items, one involving relatively low semantic distance (e.g., [blindness : sight :: deafness : ?]) and the other involving relatively high semantic distance (e.g., [blindness : sight :: poverty : ?]). The order of stimulus presentation was randomized with the constraints that no two stimuli with the same base word pair were presented consecutively, and each item was equally likely to occur before or after the other item that shared its base word pair. Only analogy items that were correctly completed by the independent raters at 90% agreement (i.e., at least 90% of raters generated the same correct solution) were used in the experiment.

fMRI Data Acquisition and Analysis

Data were collected on a 1.5 Tesla whole body scanner (General Electric Medical Systems Signa, Milwaukee, WI). For each subject, data were preprocessed, realigned, coregistered, normalized, and spatially smoothed (6 mm full width at half maximum). Functional imaging data were analyzed using the general linear model in Statistical Parametric Mapping 99 (SPM99; Friston et al., 1995), including a mixed blocked/event-related design to separate variance associated with the analogy task of interest in the present investigation from another analogy task and covariates of no interest (session mean, linear trend, and six movement parameters derived from realignment corrections). Contrast images were generated for each subject via a voxelwise t contrast analysis for comparisons between conditions and between each condition and fixation baseline. These individual contrast images were then submitted to a second-level, random-effects analysis to create group mean t images (thresholded at uncorrected $p = .0001$, including only clusters larger than 30 voxels).

Time from trial onset to solution generation button press was modeled as the solution generation event. This was the event of primary interest. Time from answer onset to trial end was modeled as a separate event type in the design matrix.

In the main parametric analysis, the semantic distance values (equal to 1 minus the pairwise term-to-term similarity value) for each of the analogies were entered to create a parametric regressor in the design matrix for each subject to test whether these values were predictive of brain activity within the a priori predicted frontopolar ROI. A general linear model incorporating task effects, a parametric regressor (indicating the semantic distance value of each analogy item), and covariates of no interest was used to compute parameter estimates (β) and *t* contrast images for each comparison at each voxel and for each subject. In this way, the height of the expected hemodynamic response function was parametrically adjusted for all analogy events as a function of the semantic distance value of each analogy. These results were then brought to a second-level random effects group analysis. Results of the parametric analysis were thresholded at uncorrected $p < .0001$ (voxel extent = 30). A small-volume correction (SVC; SVC $\alpha = .05$) within an a priori predicted ROI in frontopolar cortex was applied to a group-level statistical map of the semantic distance parametric analysis. Parametric analyses were also performed in which creativity ratings for each analogy item, difficulty ratings, and the interaction of Difficulty Ratings × Semantic Distance were taken as parametric regressors.

Results

Behavioral Findings

Response accuracy, calculated as the percentage of trials on which participants indicated generating correct solutions, was 91.75% ± 4.93%. Item analysis revealed that response accuracy and semantic distance values were marginally correlated ($r = -.22$, $p = .05$). Error trials (i.e., those for which participants indicated that the word they generated was not the same or similar to the answer word) were removed from subsequent analyses. Participants performed with a mean response time of 5,662 ms ± 645 ms ($SE = 68$ ms). Response time, calculated as the latency from the stimulus onset to the participant pressing the button to indicate that he or she had generated a solution, was positively correlated with semantic distance ($r = .35$, $p = .002$).

fMRI Findings

Frontopolar recruitment during generation of analogical solutions strengthened as a function of increasing semantic distance of analogical mapping (see Figure 2). To probe the relationship between semantic distance and frontopolar activity, we entered semantic distance values for each analogy stimulus item into the design matrix as a parametric regressor. We tested whether these values were predictive of neural activity in an a priori ROI constituting a sphere (radius = 10 mm) centered at a functional peak in left frontopolar cortex that we have previously implicated (Green, Fugelsang, Kraemer, et al., 2006; Green et al., 2010) in the mapping component of analogical reasoning (Talairach coordinates: $x = -8$, $y = 60$, $z = 26$). Small volume correction demonstrated that semantic distance positively modulated activity within this ROI, $t(22) = 6.81$, SVC $p < .05$; see Figure 2. A similarly structured parametric analysis revealed positive modulation of activity within the frontopolar ROI for rated creativity, $t(22) = 6.85$, SVC $p < .05$.

Table 1 displays the results of the main parametric semantic distance analysis over the whole brain at the exploratory threshold of uncorrected $p < .0001$. To dissociate the effect of semantic distance from difficulty, we regressed response time, correctness, and rated difficulty on semantic distance for our stimuli. We then used the set of residual variances from this multiple regression (i.e., semantic distance with difficulty partialed out) as a paramet-

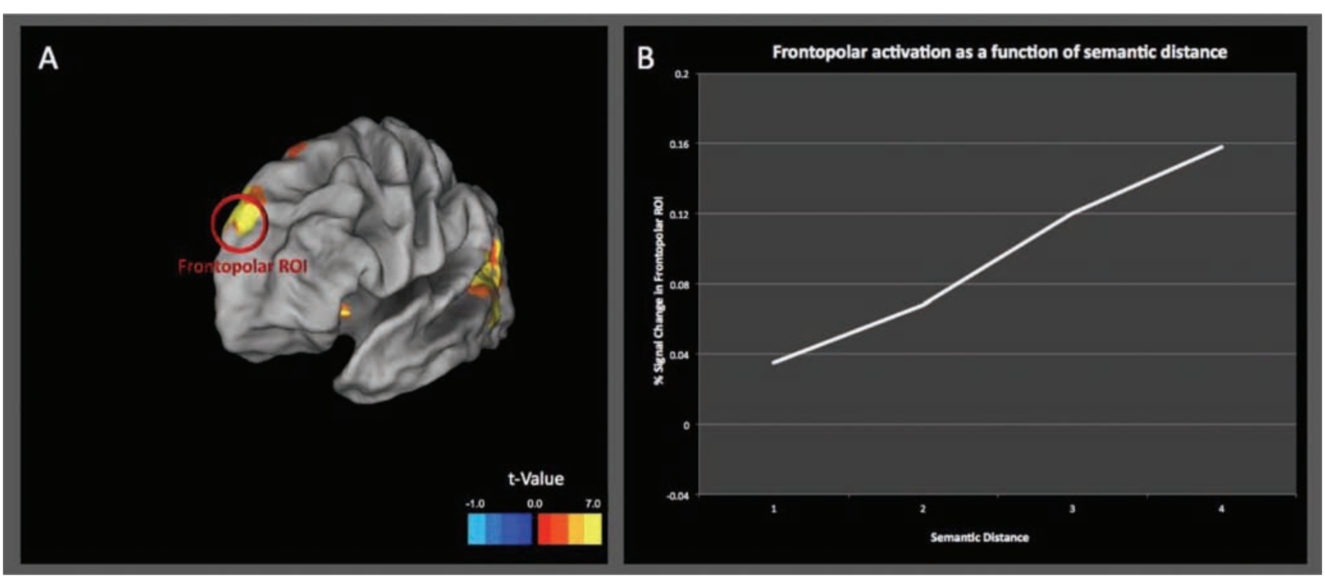

Figure 2. Neural response to semantic distance in analogical solution generation. A. Brain activity (orange) shown on an inflated cortical rendering of the left hemisphere; parametric analysis revealed regions that exhibited stronger activation for more semantically distant analogies. B. Signal change (*y*-axis) in the frontopolar region of interest increases as a function of increasing semantic distance (*z*-axis).

Table 1
Whole-Brain Parametric Analysis of Semantic Distance

Anatomical region	BA	t	Talairach coordinates x	y	z	Cluster size (no. of voxels)
Left superior frontal gyrus (frontopolar)	9/10	6.84[a]	−6	57	34	43
Left superior frontal gyrus	6	6.75	−2	20	59	41
Left superior temporal gyrus	22	5.42	−56	−59	15	45
Right caudate head		5.36	11	15	2	36
Left caudate head		5.26	−9	15	2	34

Note. All results thresholded at uncorrected $p < .0001$ (voxel extent = 30). BA = Brodmann area.
[a] Significant after small volume correction ($\alpha = .05$) within a priori frontopolar region of interest.

ric regressor in SPM99. Confirming our main parametric analysis while controlling for possible confounds, these residuals were predictive of blood oxygen level–dependent signal in the frontopolar ROI, $t(22) = 5.34$, SVC $p < .05$, strongly suggesting that difficulty-related factors do not explain the relation between semantic distance and frontopolar activity. Activity in caudate head was not significantly modulated by semantic distance after difficulty-related factors were partialed out.

Additional parametric analyses of difficulty ratings and of the interaction of Difficulty Ratings × Semantic Distance were also performed (see Table 1 in the online supplemental materials). Activity in occipital and anterior cingulate cortices is consistent with longer looking times and heightened response conflict for more difficult analogy items (Barch et al., 1997; DeYoe et al., 1996). An exploratory whole-brain contrast of activity during generation in the analogy task with baseline fixation (see Figure 3 and Table 2) revealed activity in frontopolar cortex and superior temporal gyrus (STG) as well as several additional regions previously associated with complex verbal reasoning, including anterior cingulate and left-sided ventral lateral prefrontal cortex.

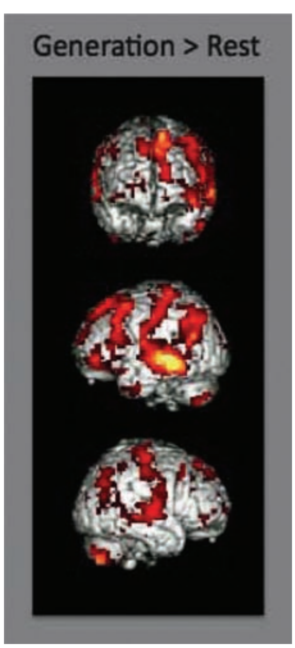

Figure 3. Exploratory whole-brain generation task > rest contrast.

Discussion

Analogical reasoning can focus creativity to generate solutions. Here, we characterized this process at the neural level. The data reveal a dose–response relationship between semantic distance and activation in left frontopolar cortex during analogical solution generation. In particular, parametric analyses revealed that semantic distance values of analogy stimuli were a significant predictor of activity within an a priori frontopolar region that we have previously implicated in analogical mapping (Green, Fugelsang, Kraemer, et al., 2006; Green et al., 2010). Critically, semantic distance of analogical mapping, not task difficulty (as assayed by response latency, correctness, and rated difficulty), modulated activity within this frontopolar ROI.

Role of Frontopolar Cortex in Analogical Reasoning

The present findings build on a growing and largely convergent body of brain-based analogy research (Bunge et al., 2005; Cho et al., 2009; Geake & Hansen, 2005; Green, Fugelsang, Kraemer, et al., 2006; Green et al., 2010; Hampshire et al., 2011; Volle et al., 2010; Wendelken et al., 2008). We have previously identified frontopolar cortex as a key mediator of relational integration during analogical reasoning (Green, Fugelsang, Kraemer, et al., 2006) and found that evaluating semantically distant analogical mappings leads to increased frontopolar recruitment (Green et al., 2010). The current data newly indicate that generating analogical solutions across semantic distance recruits the integration mechanism of left frontopolar cortex.

Interpretation of the present findings is informed by a proposed cognitive–anatomical architecture of prefrontal function (Ramnani & Owen, 2004). Within this architecture, frontopolar cortex is specialized for integration of information, including pieces of information with disparate cortical representations, which is a crucial operation for semantically distant mapping in creative analogy. We have previously reported brain-imaging evidence supporting the application of this architecture to analogical reasoning (Green, Fugelsang, Kraemer, et al., 2006). Specifically, we have shown that frontopolar cortex is preferentially recruited for the relational integration component of analogical reasoning as compared with other component processes that contribute to anal-

Table 2
Whole-Brain Contrast Generation Task > Rest

Anatomical region	BA	t	Talairach coordinates x	y	z	Cluster size (no. of voxels)
Left superior frontal gyrus (frontopolar)	9/10	7.02	−9	54	31	172
Left superior temporal gyrus	22	8.06	−54	−27	4	362
Left superior frontal gyrus	6	7.15	−8	33	54	144
Left middle frontal gyrus	11	6.99	−41	46	−12	68
Right middle occipital gyrus	19	6.54	46	−86	22	64
Left anterior cingulate gyrus	32	6.33	−1	14	36	60
Left occipital cuneus	18	6.18	−12	−80	29	58
Right cerebellum		5.81	28	−78	−29	43
Right angular gyrus	39	5.79	58	−69	32	39
Left precuneus	19	5.61	−42	−75	42	32

Note. All results thresholded at uncorrected $p < .0001$ (voxel extent = 30). BA = Brodmann area.

ogy (i.e., retrieval and alignment). Increasing cortical activity in the present investigation may reflect increasing computational demand on neuronal circuitry in frontopolar cortex as the semantic distance of analogical mapping increases.

Although a convergence on frontopolar cortex has begun to develop in the analogy brain-imaging literature, there is still great need to dissociate the cooperative but distinct contributions of multiple frontopolar subregions. Gilbert, Burgess, and colleagues have made recent contributions to this effort (Burgess, Dumontheil, & Gilbert, 2007; Gilbert, Spengler, Simons, Frith, & Burgess, 2006; Gilbert, Spengler, Simons, Steele, et al., 2006; Volle et al., 2010). A study by Volle et al. (2010) may aid in the interpretation of the present data in the context of other analogy-related frontopolar activations, which have sometimes been reported in more posterior, ventral, and lateral frontopolar areas. These authors dissociated an exploratory and representation-building phase of analogy, which recruited more posterior ventral and lateral frontopolar cortex, from an integration/mapping phase, which recruited more anterior dorsal and medial frontopolar cortex. This integration/mapping–associated activation was very near the activation we found in the present study, as well as in our previous investigations (Green, Fugelsang, Kraemer, et al., 2006; Green et al., 2010). The study by Volle et al. (2010) involved nonword stimuli composed of sets of letters, so semantic distance was not involved. However, with respect to the basic neurocognitive operations underlying analogy, their finding indicates support for the interpretation of our data as reflecting the integrative function of frontopolar cortex in analogical mapping. This interpretation is corroborated by an earlier study (Reynolds, McDermott, & Braver, 2006) that directly compared integration with retrieval from memory in a relational task that required semantic processing of verbal stimuli. A medial and dorsal left-sided region of frontopolar cortex was associated with integration, as opposed to a more posterior and lateral frontopolar region that was associated with retrieval.

In the present study, we focused on a targeted region of frontopolar cortex because we sought to test an a priori anatomical hypothesis; however, our parametric analysis of semantic distance revealed activity in several additional brain regions (see Table 1). It is a virtual certainty that multiple brain regions contribute cooperatively to creative reasoning.

In particular, the emergence of STG from parametric analyses of semantic distance in the present study as well as our recent study of analogy evaluation (Green et al., 2010) indicates this region is a likely candidate for participation in creative reasoning. The observed activity in bilateral STG is consistent with prior studies of verbal problem solving and integrating novel semantic relations during language comprehension (Bekhtereva et al., 2000; Bottini et al., 1994; Jung-Beeman et al., 2004; St George, Kutas, Martinez, & Sereno, 1999). Bilateral STG is preferentially recruited for comprehending (by reading or listening) sentences or stories, relative to comprehending single words (Bottini et al., 1994; Humphries, Willard, Buchsbaum, & Hickok, 2001; Mazoyer, Tzourio, Frak, Syrota, & Murayama, 1993; Stowe et al., 1999). STG activity has also been associated with integrating across sentences to extract themes (St George et al., 1999) and is elevated for solving word problems when the solutions involve an "aha" moment of insight (Jung-Beeman et al., 2004). STG activity in this study may also be relevant to the association of semantically distant analogical reasoning with creativity. Samco, Caplovitz, Hsieh, and Tse (2005) found that fractional anisotropy (a measure of fiber tract organization obtained from diffusion tensor imaging) of white matter connections between frontal and superior temporal cortex correlated with performance on a behavioral measure of verbal and figural creativity.

In the present study, activity in STG showed an earlier peak than did activity in frontopolar cortex (see Figure 4). This finding is consistent with prior evidence that frontopolar cortex activity peaks at greater latency than does activity in less anterior regions during relational reasoning (Crone et al., 2009). It is plausible that STG activity supports language comprehension functions that contribute to subsequent mapping operations centered in frontopolar cortex.

Relating Semantic Distance to Creativity

Consistent with our prediction, subjective ratings of the creativity of analogical mapping were highly correlated with the semantic distance values derived from latent semantic analysis. This finding supports our semantic distance metric as a factor related to creativity and is consistent with a cognitive literature that has characterized semantic distance as a primary determinant of creativity

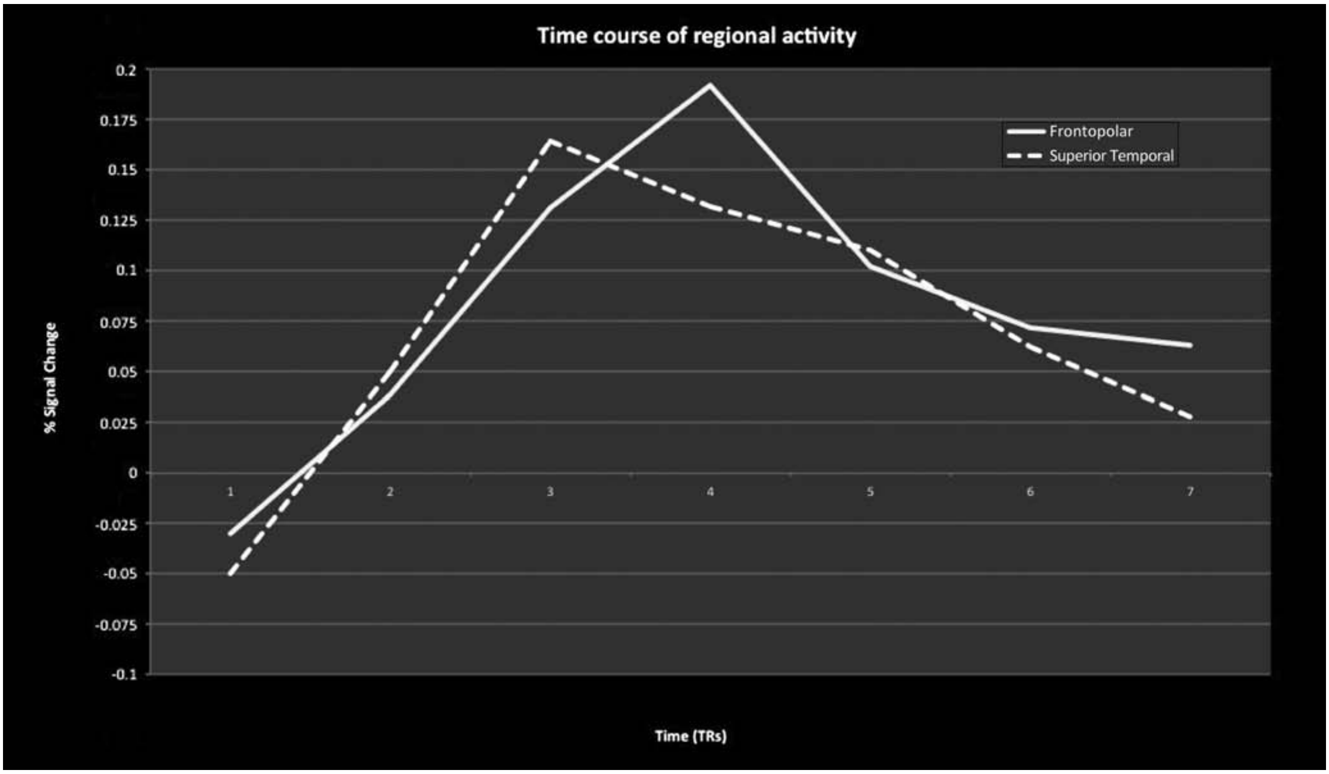

Figure 4. Regional activation time courses. Activation time courses in frontopolar cortex and superior temporal gyrus during generation in the analogy task.

in analogical mapping (Boden, 2003; Costello & Keane, 2000; Green, Fugelsang, & Dunbar, 2006; Green et al., 2008; Holyoak & Thagard, 1995; Sternberg, 1977). Our data are also consistent with a recent finding that among patients with frontotemporal dementia, creative ability depended on the integrity of frontopolar cortex (de Souza et al., 2010). Creativity as indexed by subjective ratings was a significant positive modulator of neural activity within the targeted frontopolar ROI in the present study.

Novel ideas are truly creative only if they fit relevant environmental or task-related constraints, making them useable (Mayer, 1999). Semantic distance alone would not be adequate to characterize creativity because although semantically distant ideas are usually novel, they are not necessarily appropriate. Generation of solutions in our paradigm took place within the constraints of a defined reasoning task, and the solutions generated had to be appropriate to achieve the goal of completing valid analogies. Thus, generation in this paradigm fulfills the task-appropriateness requirement of creativity. As such, the present study provides an example of the effectiveness of analogical reasoning paradigms for experimentally constraining creativity.

Dissociating Semantic Distance From Difficulty

Although the present results support the conclusion that semantic distance is related to creativity, our data indicate that semantic distance is dissociable from task difficulty at the neural level. Analyses of response latency, accuracy, and rated difficulty revealed no relation to activity in the targeted frontopolar ROI for these variables. Moreover, even after these measures of task difficulty were partialed out of our results, semantic distance still covaried positively with activity in the frontopolar ROI. This finding strongly suggests that difficulty-related factors cannot explain the relationship between semantic distance and frontopolar activity. These results are consistent with our recent findings concerning semantic distance in analogical evaluation (Green et al., 2010) and with previous work indicating that specific task demands of complex reasoning, rather than time on task or difficulty per se, account for frontopolar recruitment (Christoff et al., 2001; Geake & Hansen, 2005).

Generating Solutions Via Creative Analogy

Brain-based analogy research has typically investigated evaluation of complete analogies (e.g., is it true or false that *A* is to *B* as *C* is to *D*?). Tasks of this form are relatively straightforward to administer and have been highly informative with respect to neural mechanisms of analogical mapping and its subprocesses. However, the analogical reasoning that participants perform in these tasks does not (at least overtly) involve generating anything new. Generating something new is a fundamental element of creativity (Mayer, 1999), so these previous studies have had limited value to inform creativity research. One brain-imaging study of analogy, to our knowledge, included a condition in which words were presented in the form *A* is to *B* as *C* is to ? (Wendelken et al., 2008). That study did not investigate creativity as a parameter in analogy. As such, the authors did not differentiate stimuli with respect to creativity and did not seek to devise and pretest creative analogy items. Post hoc assessment of the creativity of the analogies included in this study is difficult because no metric of creativity or semantic distance was obtained. In their study, Geake and Hansen (2005) used nonword letter strings in a task that required participants to complete analogies. That study differed from the present study in that participants chose answers from a menu rather than generating them. Also, because the letter strings did not have meaning, semantic distance was not a relevant parameter. Nonetheless, the finding that greater differences between letter strings (with respect to alphabetical position and number of letters) predicted greater activation in anterior superior frontal gyrus is consistent with the present findings and may be related to a general parameter of distance in analogical mapping. Thus, the present study appears to be the first brain-based investigation of creativity in analogy.

Conclusions

Analogical reasoning is a core process by which creative connections that span semantic distance are formed to produce useable innovation. The present investigation demonstrates a new paradigm for studying a creativity-related factor in reasoning by parametrically manipulating semantic distance in analogical solution generation. A variety of prefrontal loci have been reported in studies of complex reasoning (Cho et al., 2009; Christoff et al., 2001; Geake & Hansen, 2005; Green, Fugelsang, Kraemer, et al., 2006; Hampshire et al., 2011; Kroger et al., 2002; Volle et al., 2010; Wendelken et al., 2008), as well as a few studies of novel and/or divergent thinking outside the constraints of a reasoning task (Carlsson et al., 2000; Howard-Jones et al., 2005). The paradigm used here offers some new clarity in the neuroscience of creative reasoning by leveraging a well-characterized form of reasoning (analogical reasoning), parametrically varying a quantifiable factor related to creativity (semantic distance), and targeting a constrained a priori brain region. Our data implicate increasing frontopolar recruitment as a neural mechanism supporting solution generation via semantically distant mapping in creative analogical reasoning.

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