

Connecting Long Distance: Semantic Distance in Analogical Reasoning Modulates Frontopolar Cortex Activity

Solving problems often requires seeing new connections between concepts or events that seemed unrelated at first. Innovative solutions of this kind depend on analogical reasoning, a relational reasoning process that involves mapping similarities between concepts. 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 characteristic of the kind of analogical mapping that can support innovation (i.e., identifying similarities across greater semantic distance reveals connections that support more innovative solutions and models). However, the neural substrates of semantically distant analogical mapping are not well understood. Here, we used functional magnetic resonance imaging (fMRI) to measure brain activity during an analogical reasoning task, in which we parametrically varied the semantic distance between the items in the analogies. Semantic distance was derived quantitatively from latent semantic analysis. Across 23 participants, activity in an a priori region of interest (ROI) in left frontopolar cortex covaried parametrically with increasing semantic distance, even after removing effects of task difficulty. This ROI was centered on a functional peak that we previously associated with analogical mapping. To our knowledge, these data represent a first empirical characterization of how the brain mediates semantically distant analogical mapping.

Keywords: analogy, anterior prefrontal, fMRI, mapping, relational integration

The importance of understanding mechanisms that support innovation has long been recognized (Sternberg 1977; Holyoak and Thagard 1995; Mayer 1999) and has recently been prioritized as imperative for scientific advancement (Schunn et al. 2006). A National Science Foundation report concluded that impending crises in science and engineering demand stronger characterization of reasoning processes that integrate concepts from disparate fields in order to identify innovative solutions (Schunn et al. 2006). Although operationalizing this directive poses experimental challenges, cognitive research has identified some factors that are likely to be relevant. For example, in analogical reasoning (e.g., Kitten is to Cat as Spark is to Fire), surface-level dissimilarity, or semantic distance, between the items being compared (e.g., the semantic distance from [Kitten:Cat] to [Spark:Fire]) characterizes the nonobvious analogical connections that can shed valuable new light (Holyoak and Thagard 1995; Green et al. 2008). Evidence from a range of fields indicates that finding semantically distant connections between items that seem different but have important underlying similarities is an effective vehicle for innovation (Holyoak and Thagard 1995; Sternberg 1997; Mayer 1999; Costello and Keane 2000; Dahl and Moreau 2002; Schunn

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et al. 2006; Green et al. 2008). Reasoning by analogy is an especially effective tool for scientists trying to identify new solutions for unexpected issues that arise in their research (Dunbar and Blanchette 2001). Analogies that bridge great semantic distances, as when Bohr envisioned the atom as a tiny solar system, have proven uniquely powerful for catalyzing innovative leaps of scientific advancement (Holyoak and Thagard 1995; Dunbar and Blanchette 2001). In consumer marketing, product development strategies based on analogical reasoning lead to products that are more innovative, more useful, and bring a higher price from consumers (Dahl and Moreau 2002). Semantic distance in analogical reasoning has also been linked to creativity (Holyoak and Thagard 1995; Boden 2003), and the solution of semantically distant analogies likely involves some of the same processes that underlie creative thinking (e.g., Green, Fugelsang, and Dunbar 2006; Green, Fugelsang, Kraemer, et al. 2006). However, despite the importance of semantically distant analogical reasoning, brain-imaging studies have not examined the parameter of semantic distance. A key question concerns the neural substrates that support integration of semantically distant concepts in the service of analogical mapping.

Here, we undertook a first neuroimaging study of semantic distance in analogical reasoning. We restricted our focus to analogical reasoning not only because it is widely considered important for supporting innovation but also because it is a constrained and well-characterized reasoning process (Sternberg 1977, 1997; Holyoak and Thagard 1995; Gentner et al. 1997; Costello and Keane 2000; Green, Fugelsang, and Dunbar 2006; Green et al. 2008). Brain-imaging studies have implicated the frontal pole of the brain in the most complex components of analogical reasoning (Bunge et al. 2005; Geake and Hansen 2005; Green, Fugelsang, Kraemer, et al. 2006; Wendelken et al. 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). A rich cognitive literature has identified mapping as the component of analogical reasoning that most directly involves bridging semantic distance (Holyoak and Thagard 1995; Barnett and Ceci 2002; Bowdle and Gentner 2005). This is because mapping is the component of analogy in which nonobvious but informative similarities are represented in order to form connections between seemingly disparate concepts.

The evidence that frontopolar cortex plays a key role in analogical mapping (Bunge et al. 2005; Geake and Hansen 2005; Green, Fugelsang, Kraemer, et al. 2006), and that analogical mapping is critical for integrating semantically distant representations (Sternberg 1977; Holyoak and Thagard 1995; Costello and Keane 2000), suggests the novel hypothesis that frontopolar cortex supports the neural integration of

semantically distant representations (e.g., relational integration in semantically distant analogies). Here, we tested and found support for this hypothesis within an a priori predicted region of interest (ROI) in frontopolar cortex. In 4-word analogy stimuli of the form “A is to B as C is to D,” we parametrically varied semantic distance values, as derived quantitatively from latent semantic analysis (Landauer and Dumais 1997; Landauer et al. 1998). That is, we varied the semantic distance from [A:B] to [C:D], over which the 2 halves of the analogy had to be integrated through analogical mapping. Parametric analyses revealed that semantic distance predicted activity in the frontopolar ROI during analogical reasoning, even after statistically removing the effect of task difficulty. Our findings, thus, provide a first brain-based characterization of semantic distance in analogical reasoning, identifying increasing frontopolar recruitment as a key mechanism.

Materials and Methods

Subjects

Twenty-three right-handed native English speakers (12 male, $M = 22.2$ 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. Eighty-four undergraduate native English speakers (18 male, $M = 21.8$ years) participated in the stimuli rating. 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 performed 120 analogy trials (see Fig. 1 and Supplementary Table S1) during 4-event-related fMRI runs. On each trial, participants indicated whether a 4-word set constituted a valid analogy (left word pair analogous to right word pair), responding “true” or “false” by button press with the index or middle finger of the right hand. The experimenter instructed that “You will have up to 8 s to respond.” Accuracy is more important than speed so try to respond as accurately as possible.” Visuospatial properties were consistent across stimuli; all stimuli were sets of exactly 4 words presented such that a 15 cm by 6 cm rectangle was formed by the midpoints of the 4 words subtending 7.5° of visual angle.

The semantic distance value for each analogy item was obtained using latent semantic analysis (Landauer and Dumais 1997; Landauer et al. 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. 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 score all analogy stimuli for difficulty (“How difficult

is it to identify the analogical connection?”). We used these ratings as a parametric regressor for subsequent fMRI analysis. Semantic distance values were correlated with rated difficulty ($r = 0.43$, $P = <0.001$).

We also obtained a binary rating for all stimuli in order to separate them into 2 classes: cross-domain analogies (involving mapping between items taken from disparate semantic domains), and within-domain analogies (involving mapping between items taken from proximal 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 (“Are the items in the left word pair taken from the same semantic domain as the items in the right word pair? That is, do the 2 word pairs involve similar kinds of things or different kinds of things”). Equal numbers of within-domain and cross-domain analogy stimuli were used. This was done to test the prediction that frontopolar cortex would reflect a proposed taxonomy in the analogy literature in which analogical reasoning is centrally divided based on the within-domain versus cross-domain distinction (Holyoak and Thagard 1995; Barnett and Ceci 2002; Bowdle and Gentner 2005). Stimuli were also established as true or false at $>90\%$ agreement. 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., [Nose:Scent]) was used on the left side in 1 trial of each stimulus type. All words were singular nouns and were equated for mean word length, number of syllables, word frequency, and concreteness for within-domain and cross-domain stimuli, using the MRC Psycholinguistic Database (Wilson 1988).

The complete set of stimuli was broken into subsets of 3 stimuli that shared the same left word-pair (1 cross-domain analogy, 1 within-domain analogy, and 1 false analogy; see Fig. 1). Trial order was pseudorandomized with the constraint that no consecutive trials shared the same left word pair (no consecutive presentations from the same 3-stimuli subset). Order was also counterbalanced such that, for example, the cross-domain analogy was equally likely to be the first, second, or third trial presented from its 3-stimuli subset.

fMRI Data Acquisition and Analysis

Data were collected on a 1.5-T 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 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 6 movement parameters derived from realignment corrections). Contrast images were generated for each subject via a voxelwise t -contrast analysis for comparisons between each pair of 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 $P = 0.001_{\text{uncorrected}}$, including only clusters larger than 30 voxels). Following calculation of these group-level contrasts, a small-volume correction (SVC; $\alpha = 0.05_{\text{SVC corrected}}$) within an a priori predicted ROI in frontopolar cortex was applied to a group-level statistical map of the cross-domain $>$ within-domain contrast.

In the main parametric analysis, the semantic distance value (equal to 1 minus the pairwise term-to-term similarity value) for each of the analogies were entered as a parametric regressor into a design matrix for each subject in order 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 $P < 0.0001_{\text{uncorrected}}$ (voxel extent = 20), and then an SVC was applied within the frontopolar ROI

Cross-Domain Analogy	Within-Domain Analogy	False Analogy
Nose Antenna + Scent Signal	Nose Tongue + Scent Taste	Nose Eyelash + Scent Mascara

Figure 1. Example stimuli. The figure displays examples of the 3 classes of trials presented to participants during fMRI. The same word pair appeared on the left side in 1 trial of each class.

($\alpha = 0.05_{\text{SVC corrected}}$). Additionally, several similar parametric analyses, thresholded at a less conservative threshold ($P < 0.01_{\text{uncorrected}}$), were performed in which response times, mean percent correct, and rated difficulty for each analogy item were taken as regressors to determine whether factors related to difficulty were significant modulators of activity in frontopolar cortex.

Results

Behavioral Findings

Participants performed at a response accuracy level of $92.97\% \pm$ standard deviation (SD) = 4.62%, standard error (SE) = 0.42% overall, $92.52\% \pm$ SD = 4.21%, SE = 0.47% for true trials, and $93.91\% \pm$ SD = 5.38%, SE = 0.85% for false trials. Item analysis revealed that response accuracy and semantic distance values were not correlated ($r = -0.18$, $P = 0.11$). Participants performed with a mean response time of $4780 \pm$ SD = 503, SE = 54 ms overall, $4493 \pm$ SD = 430, SE = 51 ms for true trials, and $5354 \pm$ SD = 591, SE = 93 ms for false trials. Response time was positively correlated with semantic distance ($r = 0.36$, $P = 0.001$).

fMRI Findings

Frontopolar recruitment strengthened as a function of increasing semantic distance of analogical mapping (see Fig. 2). In order to probe the relationship between semantic distance and frontopolar activity, semantic distance values for each analogy stimulus item were entered 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 in the mapping component of analogical reasoning (Green, Fugelsang, Kraemer, et al. 2006; Talairach coordinates: $x = -8$, $y = 60$, and $z = 26$). An SVC demonstrated that semantic distance positively modulated activity within this ROI ($t = 6.46$, $P < 0.05_{\text{SVC corrected}}$; see Fig. 2).

Table 1 displays the results of the main parametric semantic distance analysis over the whole brain at the exploratory threshold of $P < 0.0001_{\text{uncorrected}}$.

To dissociate the effect of semantic distance from difficulty, we regressed response time, correctness, and rated difficulty against semantic distance for our stimuli. We then used the set

of residual variances from this multiple regression (i.e., values representing semantic distance with difficulty partialled out) as a parametric regressor in SPM. Confirming our main parametric analysis while controlling for possible confounds, these residuals were predictive of blood oxygen level-dependent signal in the frontopolar ROI ($t = 5.07$, $P < 0.05_{\text{SVC corrected}}$), strongly suggesting that difficulty-related factors cannot explain the relation between semantic distance and frontopolar activity. Activity in anterior cingulate, caudate head, and inferior occipital gyrus was not significantly modulated by semantic distance after difficulty-related factors were partialled out.

As an additional examination of semantic distance in analogical mapping, we tested the neural bases of a central distinction in the analogical reasoning literature between 2 types of analogies (Barnett and Ceci 2002; Bowdle and Gentner 2005; Green, Fugelsang, and Dunbar 2006; Green et al. 2008). Analogies were classified as either cross-domain or within-domain by independent rating. A direct comparison revealed that cross-domain analogies were associated with significantly greater recruitment of the frontopolar ROI than within-domain analogies ($t = 3.52$, $P < 0.05_{\text{SVC corrected}}$). This contrast corroborates the main parametric analysis because cross-domain analogies had significantly higher semantic distance values than within-domain analogies, $t(118) = 11.6$, $P < 0.001$). However, the parametric relationship between semantic distance and frontopolar activity was significant even when restricting parametric analysis to only cross-domain analogy trials or only within-domain trials. That is, separate analyses for within-domain and cross-domain analogies revealed that semantic distance was a significant positive modulator of activity in the frontopolar ROI ($P < 0.05_{\text{SVC corrected}}$) for both classes of analogy.

Also corroborating the main parametric analysis, separate analyses indicated that semantic distance positively modulated activity in the frontopolar ROI for both true ($t = 6.82$, $P < 0.05_{\text{SVC corrected}}$) and false ($t = 4.93$, $P < 0.05_{\text{SVC corrected}}$) trials. A direct contrast revealed that frontopolar activity was greater for true trials than false trials at a marginally significant level ($t = 3.14$, $P < 0.06_{\text{SVC corrected}}$), putatively because analogical mapping on true trials involved a greater relational integration component (see Green, Fugelsang, Kraemer, et al. 2006 for a discussion of this issue).

To further assess possible confounds between semantic distance and difficulty, each participant's response times for

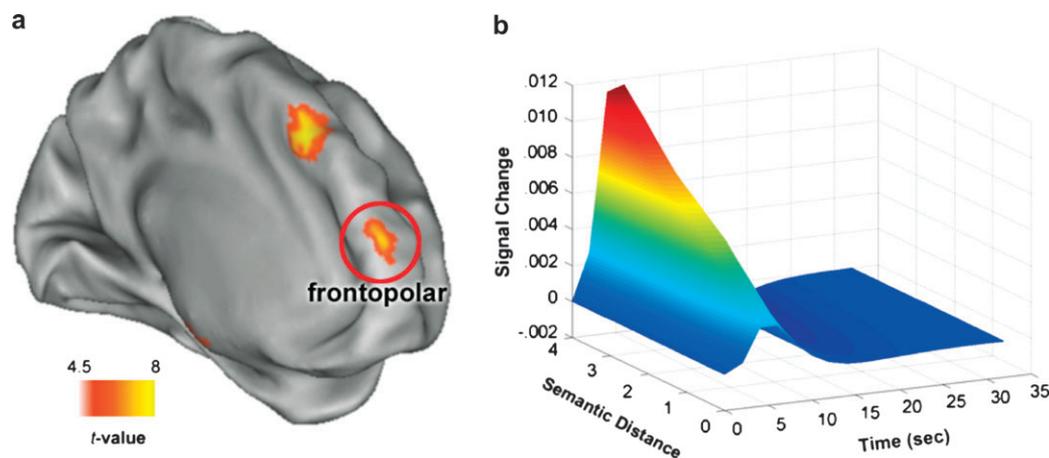


Figure 2. Neural response to semantic distance in reasoning. (A) Brain activity (orange) shown on an inflated cortical rendering of the left hemisphere; parametric analysis revealed regions that exhibited stronger activation for more semantically distant analogies. (B) Signal change (y axis) in the frontopolar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

Table 1

Whole-brain parametric analysis of semantic distance

Anatomical region	Brodmann area	<i>t</i>	Talairach coordinates			Cluster size, voxels (<i>n</i>)
			<i>x</i>	<i>y</i>	<i>z</i>	
Left superior frontal gyrus (frontopolar)	9/10	6.46 ^a	-12	58	26	33
Left anterior cingulate gyrus	32	6.32	-5	29	24	57
Left STG	22	6.85	-45	26	-1	53
Right STG	22	6.36	36	26	-6	21
Left IFG	45	7.05	-52	19	16	33
Left caudate head	8	6.25	-12	15	0	24
Right inferior occipital gyrus	18	8.02	37	-83	-5	20

Note: All results thresholded at $P < 0.0001_{\text{uncorrected}}$ (voxel extent = 20).^a Significant after SVC ($\alpha = 0.05$) within a priori frontopolar ROI.

each of the analogy stimuli were incorporated as a parametric regressor at the individual subject level. These results were then brought to the group level prior to computation of the group-level semantic distance parametric analysis. An exclusionary mask derived from the response time parametric analysis at a nonconservative threshold of $P < 0.01_{\text{uncorrected}}$ and applied to the semantic distance parametric analysis revealed that response time did not modulate activity in any voxel within the frontopolar ROI. This analysis indicates that preferential recruitment of frontopolar cortex for more semantically distant analogies is not due to greater response time. Similarly, structured parametric analyses based on rated difficulty, and mean percentage correct for each analogy item also revealed no significantly modulated voxels with the frontopolar ROI.

Discussion

The present findings provide a first empirical characterization of how the brain mediates semantically distant analogical mapping. Our data implicate a direct relationship between semantic distance of analogical mapping and commensurate recruitment of frontopolar cortex. In particular, parametric analyses revealed that semantic distance values of analogy stimuli were significantly predictive of activity within an a priori frontopolar region previously implicated in analogical mapping (Green, Fugelsang, Kraemer, et al. 2006). Critically, semantic distance of analogical mapping, and not task difficulty (as assayed by response time, correctness, and rated difficulty), modulated activity within this frontopolar ROI.

Relational Integration and Broader Functionality of Frontopolar Cortex

Our findings support a general rostrocaudal hierarchy of PFC organization, which is empirically indicated by a growing body of research (Christoff and Gabrieli 2000; Braver and Bongiolatti 2002; Bunge et al. 2003; Koechlin et al. 2003; Badre and D'Esposito 2007). One account, which is broadly consistent with the present findings, holds that information is derived from external stimuli (e.g., 4-word sets) at relatively caudal areas of supramodal cortex, and internal representations generated from this information are integrated through more abstract cognitive operations (e.g., analogical mapping) mediated by frontopolar cortex (also called rostral prefrontal cortex; Christoff and Gabrieli 2000; Gilbert, Spengler, Simons, Steele, et al. 2006; Burgess et al. 2009).

Interpretation of the present findings is most directly informed by a cognitive-anatomical architecture of prefrontal cortex proposed by Ramnani and Owen (2004). This architecture unifies a range of evidence concerning frontopolar cortex, considering functional brain-imaging findings in the context of the histological properties and connectivity of this region. The authors note that the extent of arborization of neurons in frontopolar cortex (number of dendritic spines per cell and spine density) is greater than in comparable areas of frontal cortex, whereas the density of cell bodies is substantially less. They suggest that this structure indicates an integrative mechanism. In particular, one of the major integrative functions ascribed to frontopolar cortex is integration of relations for reasoning (Christoff et al. 2001; Ramnani and Owen 2004; Waltz et al. 2004), which is the cognitive operation instantiated by analogical mapping (e.g., Gilbert, Spengler, Simons, Steele, et al. 2006).

The present findings build on this architecture and on our previous work implicating frontopolar cortex in relational integration during analogical reasoning and other complex cognition. Specifically, the data newly demonstrate that the relational integration mechanism of frontopolar cortex is sensitive to the semantic distance across which representations must be integrated. As such, our findings implicate degree of frontopolar activation as a marker of semantic distance in analogical reasoning. Increasing cortical activity may reflect increasing computational demand placed on the neuronal integration network of frontopolar cortex commensurate with relational integration across increasing semantic distance.

Prior studies have reported frontopolar activation elicited by nonverbal reasoning tasks. These studies have employed object matrices and strings of alpha-numeric characters of varying complexity (Christoff et al. 2001; Kroger et al. 2002; Raven et al. 2003; Geake and Hansen 2005; Smith et al. 2007). Activity reported in these nonverbal paradigms have varied somewhat, but has consistently involved bilateral foci. By contrast, the present study found unilateral left-sided activation associated with our verbal reasoning task. This finding is consistent with prior reports of left-lateralized frontopolar activity associated with verbal analogical reasoning (Bunge et al. 2005; Gilbert, Spengler, Simons, Steele, et al. 2006). Moreover, foci reported in studies of nonverbal reasoning have typically been caudal to the ROI investigated in the present study, which was initially identified in our previous study of verbal analogy (Gilbert, Spengler, Simons, Steele, et al. 2006). These differences may reflect a distinction between semantic distance and the relational complexity variable (number of terms to be integrated in relational reasoning; Halford et al. 1998), which was manipulated in prior nonverbal stimuli, or they may reflect the more general verbal versus nonverbal modality distinction. The extent to which prior, nonverbal paradigms may have varied a form of semantic distance is not clear, although this possibility seems at least plausible given the stimuli employed in those paradigms (Christoff et al. 2001; Kroger et al. 2002; Geake and Hansen 2005).

In any circumstance, the present data do not indicate against relational complexity as a modulator of frontopolar activity, especially for nonverbal reasoning. Indeed, it is likely that an umbrella term, such as relational flexibility, which includes relating/integrating terms across semantic distance, as well as processing relational complexity, might provide a more complete sense of the range of cognitive demands that modulate activity in frontopolar cortex. This view is consistent with the adaptive coding model of prefrontal cortex proposed by Duncan

(2001), which describes neuronal function in prefrontal cortex as flexibly adaptable to task demands, and predicts stronger focal activation as the level of demand increases. In particular, the statistical, rather than absolute, regional specificity of prefrontal cortex delineated in this model may help to explain why reported frontopolar loci have been nearby each other, but not precisely colocalized, for similar but nonidentical reasoning tasks (Christoff et al. 2001; Kroger et al. 2002; Gilbert, Spengler, Simons, Steele, et al. 2006; Wendelken et al. 2008).

Cross-Domain Analogies versus within-Domain Analogies

The finding that cross-domain analogies elicited stronger frontopolar recruitment than within-domain analogies addresses a central question in the analogy literature concerning whether and how the within-domain versus cross-domain distinction is reflected at the neural level (Barnett and Ceci 2002; Bowdle and Gentner 2005; Green, Fugelsang, and Dunbar 2006, 2008). The differential recruitment of left frontopolar cortex identified in the present study provides the first brain-based support for a proposed taxonomy of analogical reasoning, in which the within-domain versus cross-domain distinction is the primary structural division (Barnett and Ceci 2002). The data indicate that frontopolar cortex is recruited more strongly for the mapping of cross-domain analogies than within-domain analogies (Barnett and Ceci 2002; Bowdle and Gentner 2005; Green, Fugelsang, and Dunbar 2006; Green et al. 2008).

At a finer grain, separate parametric analyses for within-domain and cross-domain analogies revealed that the parameter of semantic distance positively modulated frontopolar activation for analogies in both classes ($P < 0.05_{\text{SVC}}$ corrected for both analyses). Thus, the correlation between frontopolar recruitment and semantic distance was not simply due to the cross-domain versus within-domain distinction. Although frontopolar activity broadly reflects a taxonomic distinction between these classes of analogy, the mechanism of frontopolar recruitment appears to operate at a level of sensitivity that is more fine grained than a single gross dichotomy.

Dissociating Semantic Distance from Difficulty

The present data indicate that semantic distance is dissociable from task difficulty at the neural level. Parametric analyses of response time, accuracy, and rated difficulty revealed no activity in the targeted frontopolar ROI due to these variables. Moreover, even after these measures of task difficulty were partialled out of our results, semantic distance still covaried positively with activity in the frontopolar ROI. These findings strongly suggest that difficulty-related factors cannot explain the relation between semantic distance and frontopolar activity. These results are consistent 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 and Hansen 2005). In addition, stimuli in the present study were equated for visuospatial properties and word length (see Materials and Methods section), so visuospatial complexity does not account for the observed modulation of frontopolar cortex.

ROI-Based Hypothesis Testing

One of the challenges of studying the neural bases of high-level cognitive function is the difficulty of constraining predictions and replicating/colocalizing brain regions across different

studies. As noted above, even within the set of investigations reporting frontopolar recruitment associated with relational reasoning, loci of activation have varied (Christoff and Gabrieli 2000; Braver and Bongiolatti 2002; Bunge et al. 2003, 2005; Koechlin et al. 2003; Gilbert Spengler, Simons, Frith, and Burgess 2006; Burgess et al. 2009). Each of these findings has contributed to a better understanding of the functions of this brain region. Nonetheless, the extent to which the cognitive operations associated with different reported loci are overlapping or distinct is still largely unresolved (Gilbert, Spengler, Simons, Steele, et al. 2006). Here, we directly tied the present work to our previous findings (Green, Fugelsang, Kraemer, et al. 2006) by making a targeted prediction constrained by a previously reported peak of functional activation in frontopolar cortex. As such, the present research provides support for the practicability of ROI-based hypothesis testing in studies of high-level cognition.

Beyond Frontopolar Cortex

Although our central hypothesis concerned activation in the targeted frontopolar region that we previously implicated in analogical mapping, our parametric analysis of semantic distance revealed several additional activating regions (Table 1). It is possible that these regions directly or indirectly contribute to the neural processing of semantically distant analogies. The observed activity in bilateral superior temporal gyrus (STG), for example, is consistent with prior studies of verbal problem solving and integrating novel semantic relations during language comprehension (Bottini et al. 1994; St George et al. 1999; Bekhtereva et al. 2000; Jung-Beeman et al. 2004). Bilateral STG is preferentially recruited for comprehending (by reading or listening) sentences or stories, relative to comprehending single words (Mazoyer et al. 1993; Bottini et al. 1994; Stowe et al. 1999; Humphries et al. 2001). 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 putative association of semantically distant analogical reasoning with creativity (Holyoak and Thagard 1995; Boden 2003). Samco et al. (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.

The activity we observed in left-sided inferior frontal gyrus (IFG) may also reflect increasing semantic distance of analogical reasoning, putatively as a result of greater semantic elaboration (Wagner et al. 1998; Wig et al. 2004), and increasing selection demand (Thompson-Schill et al. 1997; Badre et al. 2005). Previous analogy research has suggested that, because cross-domain analogies require the reasoner to formulate abstract connections between systems that do not have obvious similarities, cross-domain analogies elicit greater semantic elaboration than within-domain analogies (Chen 1999; Blanchette and Dunbar 2002; Didierjean and Nogy 2004). Semantic elaboration is an established strategy for enhancing learning and remembering (Wagner et al. 1998; Davachi et al. 2001), and likely contributes to the effectiveness of analogy as a teaching tool (Donnelly and McDaniel 1993). Brain-based memory research

has implicated left IFG as centrally involved in semantic elaboration (Kapur et al. 1994; Wagner et al. 1998; Wig et al. 2004). The present finding that IFG was preferentially recruited for more semantically distant analogies is consistent with this literature.

The IFG finding in the present study also accords with a growing literature concerning the role of IFG in selecting among semantic representations. IFG (specifically dorsal BA 44/45) is reliably associated with tasks that require choosing among words or objects along some semantic dimension (e.g., color, size, expense, and similarity). Across studies, IFG has been preferentially recruited for higher versus lower selection demand conditions, indicating that increasing activity in IFG supports a task-general selection process (i.e., identifying the correct alternative amid ambiguity or competition; Thompson-Schill et al. 1997, 1998). Based on this literature, we might expect greater IFG activity for more semantically distant analogies if the valid analogical mapping is more ambiguous (e.g., more selection demand in identifying the correct mapping among possible alternatives that participants mentally generate in evaluating whether 4-word sets constitute valid analogies). Indeed, this is what we observed in IFG as participants arrived at their true/false judgments about the presented 4-word sets.

For the reasons noted here, it is not surprising to find that IFG activity tracks with semantic in our stimuli. Nonetheless, the literatures concerning frontopolar cortex and IFG indicate that these regions likely serve different functions, with frontopolar cortex being more involved in relational integration across semantic distance, and IFG being more involved in semantic elaboration and selection processes.

Both the IFG and STG findings in the present study underscore the importance of taking a network approach to studying the neural basis of analogical reasoning and other high-level cognitive constructs. The present study focused on a targeted region of frontopolar cortex because we sought to test an a priori anatomical hypothesis. However, it is a virtual certainty that multiple brain regions contribute cooperatively to semantically distant analogical reasoning, and STG and IFG appear to be likely contributors.

Some of the observed activations may reflect parameters other than semantic distance. Occipital activity, for example, is likely to reflect longer looking times for more semantically distant analogies. When response time was partialled out from semantic distance, this activity no longer surpassed the exploratory whole-brain threshold of $P < 0.0001$. Anterior cingulate activity is likely a reflection of increasing response conflict (i.e., whether to respond true or false) on more semantically distant analogy trials (Barch et al. 2000; MacDonald et al. 2000; Braver et al. 2001; Botvinick et al. 2004). This activity also failed to reach the whole-brain exploratory threshold after partialling out difficulty-related factors from semantic distance.

Conclusions

The present investigation demonstrates a novel paradigm in reasoning research and offers some new clarity in the neuroscience of cognition that supports innovation. This paradigm leverages a well-characterized form of reasoning (i.e., analogical reasoning), parametrically varies a quantifiable factor identified as important for innovative outcomes (i.e., semantic distance), and targets a constrained a priori brain region (i.e., frontopolar cortex). Our data implicate increasing

frontopolar recruitment as a neural mechanism for integrating relations across semantic distance in analogical mapping. This finding indicates a role for frontopolar cortex in supporting analogical connections that lead to innovative outcomes (Holyoak and Thagard 1995; Mayer 1999).

Supplementary Material

Supplementary Table S1 can be found at: <http://www.cercor.oxfordjournals.org/>.

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