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Introduction to the Special Section on the Neural Substrate of Analogical Reasoning and Metaphor Comprehension

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The special section on the neural substrate of relational reasoning includes 4 articles that address the processes and brain regions involved in analogical reasoning (Green, Kraemer, Fugelsang, Gray, & Dunbar, 2011; Maguire, McClelland, Donovan, Tillman, & Krawczyk, 2011) and in metaphor comprehension (Chettih, Durgin, & Grodner, 2011; Prat, Mason, & Just, 2011). We see this work as an example of how neuroscience approaches to cognition can lead to increased understanding of cognitive processes. In this brief introduction, we first situate the 4 articles in the context of prior cognitive neuroscience work on relational reasoning. We then highlight the main issues explored in these articles: different sources of complexity and difficulty in relational processing, potential differences between the roles of the 2 hemispheres, and the impact of individual differences in various cognitive abilities. The 4 articles illustrate a range of methodologies, including functional magnetic resonance imaging (fMRI; Green et al., 2011; Prat et al., 2011), event-related potentials (ERPs; Maguire et al., 2011), and different types of semantic priming (Chettih et al., 2011; Prat et al., 2011). They highlight the connections between research on analogy and on metaphor comprehension and suggest, collectively, that a cognitive neuroscience approach to relational reasoning can lead to converging conclusions.

Keywords: analogy, metaphor, hemispheric asymmetries, ERP, fMRI

For at least four decades, research on attention, memory, language, and visual processes has been increasingly informed by the approach of cognitive neuroscience. This new approach has led to fundamental changes in our understanding of cognitive processes. For example, surprising links have been found between motor control and categorization, processes previously viewed as unrelated (Mahon & Caramazza, 2008). In some cases brain regions not previously thought to be involved in a cognitive process have turned out to be relevant, as in the case of the parietal lobes and memory (Olson & Berryhill, 2009).

More specifically, over the past 15 years or so, cognitive neuroscience has begun to enrich our understanding of higher level cognition. The earlier research on attention, memory, perception, and language laid the foundation for the current cognitive neuroscience approach to higher level cognition. In addition to proposing potential functions of various regions of the brain (e.g., Milner, 1963), the earlier work identified key pathways underlying cognitive processes, such as the dorsal and ventral streams (Ungerleider & Mishkin, 1982) and basic methods in cognitive neuroscience (for a review, see Posner, 2004). Not only has work in cognitive neuroscience identified which brain areas are involved in which types of cognitive processes, but it has also shown how the same brain areas may have multiple functions. In particular, neuroscientists have started to identify the neural pathways that are involved in higher level cognitive processes such as analogy and metaphor or, more generally, relational reasoning (Holyoak, in press).

There is now a growing body of research focused on the neural substrate of the processes involved in tasks such as analogical reasoning and metaphor comprehension. We see this work as an example of how neuroscience approaches to cognition can lead to increased understanding of cognitive processes and also to a new way of building integrative theories. Early work on the neural basis of analogical reasoning linked the integration of relations to functions of the prefrontal cortex (Robin & Holyoak, 1995; Waltz et al., 1999). Studies using functional magnetic resonance imaging (fMRI) found evidence that the anterior lateral surface of the prefrontal cortex (rostrolateral PFC) plays an especially important role in relational processing, both with nonverbal reasoning tasks (Christoff et al., 2001; Kroger et al., 2002; Prabhakaran, Smith, Desmond, Glover, & Gabrieli, 1997) and with verbal analogy problems (Bunge, Wendelken, Badre, & Wagner, 2005; Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006; for a review, see Ramnani & Owen, 2004). More recently, studies have begun to dissociate important subprocesses involved in analogical processing (Cho et al., 2010), including possible hemispheric asymmetries (Bunge, Helskog, & Wendelken, 2009; for a review, see Knowlton

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& Holyoak, 2009). Similar issues have arisen in research on the neural basis of metaphor comprehension (for a meta-analysis of neuroimaging studies, see Ferstl, Neumann, Bogler, & von Cramon, 2008). The comprehension of novel metaphors seems particularly likely to share component processes with verbal analogy tasks that involve semantically distant relations (Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010).

Most studies of the neural basis of relational processing have appeared in journals oriented more toward neuroscience than psychology. In this special section, we present four articles that illustrate how the cognitive neuroscience approach may be used to address basic theoretical issues in higher cognition, focusing on analogical reasoning and metaphor comprehension. An important goal of the special section is to highlight the connections between these two areas of research, which have often been unduly isolated from one another. Collectively, these articles suggest that relational reasoning involves many different brain regions working in concert, setting the stage for future research aimed at specifying the neural pathways that give rise to complex cognitive processes.

In different ways, each of the articles addresses issues related to cognitive theories of relational processing. The articles by Green, Kraemer, Fugelsang, Gray, and Dunbar (2011) and by Maguire, McClelland, Donovan, Tillman, and Krawczyk (2011) used different methods (fMRI and event-related potentials [ERPs], respectively) but a similar design: presenting components of an analogy at different points in time and measuring brain activity. This basic paradigm of sequential presentation can be traced back to classic work by Sternberg (1977), and the role of different phases in solving four-term analogy problems has a long history in work on intelligence (Spearman, 1927). The article by Green et al. demonstrates that a similarity measure based on a well-known cognitive tool, latent semantic analysis (Landauer & Dumais, 1997), predicts the amount of activation in frontopolar cortex during analogical reasoning and suggests this area is a new component of creative cognition. Furthermore, the finding of bilateral activation in the superior temporal gyrus during analogical reasoning ties in with work on metaphor and demonstrates key links between analogy, metaphor, and creativity.

An important issue is the extent to which the processes involved in relational reasoning are specific to relational processing or shared with other types of cognitive processing. For example, how are analogical "mismatches" detected? Maguire et al. (2011) find that the same ERP signature, N300/400, is generated both by detection of analogical incongruity and by other types of semantic and perceptual incongruity. This result reinforces evidence that relational reasoning recruits processes that are used in many different tasks, rather than being entirely unique to the relational mind. Furthermore, the Maguire et al. article, in conjunction with the three other articles, suggests the importance of developing models that incorporate the temporal sequence of cortical events during relational reasoning.

The articles by Prat, Mason, and Just (2011) and by Chettih, Durgin, and Grodner (2011) focus on metaphor comprehension. These two articles highlight the ways that metaphor comprehension may vary depending on contextual information and prior experience. The Prat et al. article directly addresses the relationship between the processes involved in metaphor comprehension and in analogical reasoning. In the cognitive literature, there has been disagreement about the extent to which metaphor comprehension does (Gentner, Bowdle, Wolff, & Boronat, 2001) or does not (Glucksberg, 2003) depend on analogical mapping. In the cognitive neuroscience literature, neuroimaging studies have found that anterior regions in *left* prefrontal cortex are selectively activated during analogical processing (Bunge et al., 2009; Green et al., 2010). In contrast, early neuropsychological studies emphasized the importance of the *right* hemisphere in metaphor comprehension (e.g., Brownell, Simpson, Bihrle, Potter, & Gardner, 1990). If there were indeed strong hemispheric differences between the loci of analogical mapping and metaphor comprehension, such a dissociation would suggest the latter process does not require the former.

However, Prat et al. (2011) review evidence suggesting that the brain regions involved both in analogy and in metaphor comprehension are modulated by various factors such as novelty, complexity, and familiarity, as well as by individual differences in cognitive ability. By integrating fMRI methods with priming techniques and individual-difference measures, Prat et al. show that the left hemisphere is involved in metaphor comprehension as well as in analogical reasoning and that the right hemisphere becomes involved due to a kind of "spillover" when task demands are high. Thus, this study lends support to the view that metaphor comprehension, at least when difficulty is high, depends on analogical mapping.

The Chettih et al. (2011) article lends new support to recent theories of lateralization in metaphor comprehension (Mashal & Faust, 2009; Schmidt, Kranjec, Cardillo, & Chatterjee, 2009), which correspond to the *career of metaphor* model of Bowdle and Gentner (2005). According to this model, conventional metaphors are processed as if they were established categories, whereas novel and more complex metaphors are more likely to involve analogical comparison. Using a divided visual-assessment technique and a carefully controlled set of priming metaphors, Chettih et al. found that the left and right hemispheres are differentially involved in the processing of conventional versus novel metaphors. In particular, conventional metaphors have an advantage when they are processed in the left hemisphere but lose this advantage when they are processed in the right hemisphere. By contrast, the right hemisphere facilitates flexible construction of meaning for novel metaphors. The authors suggest that this flexibility in the right hemisphere allows for the construction of alternative structural alignments, which may be more or less available under various interpretive contexts. They further propose that the flexibility of the right hemisphere is consistent with various models of analogy that operate using some type of constraint-satisfaction mechanism (e.g., Hummel & Holyoak, 1997, 2003).

The articles illustrate a range of methodologies, including fMRI (Green et al., 2011; Prat et al., 2011), electrophysiology (Maguire et al., 2011), and different types of semantic priming (Chettih et al., 2011; Prat et al., 2011). The studies collectively explore issues related to different sources of complexity and difficulty in relational processing, potential differences between the roles of the two hemispheres, and the impact of individual differences in various cognitive abilities. These four articles suggest that a cognitive neuroscience approach to relational reasoning, taking advantage of multiple methodologies, can lead to converging conclusions.

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