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Review

The cognition and neuroscience of relational reasoning

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A R T I C L E I N F O

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A B S T R A C T

There has been a growing interest in understanding the complex cognitive processes that give rise to human reasoning. This review focuses on the cognitive and neural characteristics of relational reasoning and analogy performance. Initially relational reasoning studies that have investigated the neural basis of abstract reasoning with an emphasis on the prefrontal cortex are described. Next studies of analogical reasoning are reviewed with insights from neuropsychological and neuroimaging studies. Additionally, studies of cognitive components in analogical reasoning are described. This review draws together insights from numerous studies and concludes that prefrontal areas exhibit domain independence in relational reasoning, while posterior areas within the temporal, parietal, and occipital lobes show evidence of domain dependence in reasoning. Lastly, future directions in the study of relational reasoning are discussed.

Contents

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Abbreviations: DLPFC, dorsolateral prefrontal cortex; ERP, event-related potential; fG, fluid General Intelligence; FTLD, frontotemporal lobar degeneration; fMRI, functional Magnetic Resonance Imaging; MRI, Magnetic Resonance Imaging; MFG, middle frontal gyrus; PET, positron emission tomography; PFC, prefrontal cortex; RLPFC, rostrolateral prefrontal cortex; RPM, Raven's Progressive Matrices; TBI, traumatic brain injury

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1. Introduction

Reasoning has been of interest to cognitive psychologists for many years and research has been driven primarily by attempts to understand basic problem solving in healthy adult humans. These studies date back to the Gestalt tradition and carried on through the rise of the cognitive approach to psychological inquiry. Relational reasoning has been considered to be an important domain for assessments of fluid intelligence (Spearman, 1904). Prominent examples of this approach such as the Raven's matrices (Raven, 1938), and the Cattell Culture Fair test (1973) are comprised of abstract novel pattern match problems that are not strongly dependent on prior knowledge. Research in cognitive psychology and cognitive science has been highly active over the past several decades with numerous theoretical papers outlining key processes in relational reasoning with a particular emphasis on analogy (Gentner, 1983; Gick and Holyoak, 1983; and Sternberg and Rifkin, 1979). This work led to the development of computational models of relational reasoning (Falkenhainer et al., 1989; Holyoak and Thagard, 1989; Hofstadter, 1995; and Hummel and Holyoak, 1997, 2003). With the establishment of many of the important cognitive operations involved in reasoning, the field has increasingly begun to place the reasoning abilities of healthy adult humans into both cross-species and lifespan developmental contexts. Such integrative approaches have suggested key cognitive capacities that appear to be building blocks for abstract reasoning.

Analogies are important for making sense of novel incoming information based on what has been experienced in the past. Understanding the relations among people, animals, or objects in a situation are critical for drawing successful analogies. This ability to make relational comparisons across domains of knowledge is representative of the elaborated problem solving ability observed in humans. Notably, the cognitive skills needed to detect and map relations improve with age (Goswami, 2001; Holyoak et al., 1984; and Rattermann and Gentner, 1998). As adults, we are able to use analogies to both understand novel situations and to suit our goals in teaching others and highlighting similarities between situations. Blanchette and Dunbar (2001) summarized the types of analogies observed in real world environments such as science lab meetings and in news media. Molecular biologists were observed to use analogies when confronting novel data by referring to known phenomena within their field (Dunbar, 1997). Conversely, politicians have been observed to use analogies between policy situations and remote domains such as magical explanations (Dunbar and Blanchette, 2001). Furthermore, the political analogies tended to involve emotional content to advance political goals. Thus, analogies may be used in both understanding new information and in teaching others about aspects of situations that may be seen as similar. Analogical thinking has also been invoked in the explanations of diverse higher order cognitive abilities including empathy (Barnes and Thagard, 1997), theory of mind (Lillard, 1999), metaphor (Gentner et al., 2001), and mathematics (Novick and Holyoak, 1991; Richland et al., 2007). Thus analogy is a core cognitive ability that serves as a rich tool for human thinking.

From a laboratory-based perspective, an important advance has been to investigate the neural basis of these cognitive building blocks. Major cognitive subcomponents of reasoning include working memory capacity, inhibitory control, and the ability to shift attention toward relevant details and away from inappropriate ones. These aspects are developed through childhood to enable adults to use increasingly abstract representations in their reasoning. Further, these cognitive component processes can be assessed across-species, giving further clues as to what constitutes human reasoning and how it differs from other species.

The cognitive processes involved in relational reasoning have been further identified and specified through investigations of neural processing related to these functions. Notably, the progress in functional brain imaging has enabled the study of higher cognitive reasoning processes. These include studies of deductive reasoning (Goel and Dolan, 2000; Monti et al., 2007), analogical reasoning (Bunge et al., 2005; Green et al., 2006; Krawczyk et al., 2010a; and Luo et al., 2003), as well as neuropsychological studies of problem solving (Goel and Grafman, 1995), and chess cognition (Campitelli et al., 2007). An emerging consensus from many of these studies is that the prefrontal cortex (PFC) contributes extensively to reasoning ability (Robin and Holyoak, 1995). Through improvements in understanding both the functions of the PFC and how they enable abstract reasoning to occur, we are in a position to further refine our understanding of what cognitive factors are involved in reasoning and further constrain models of reasoning.

Another promising avenue in reasoning research is to study the effects of brain damage and disease on reasoning abilities. This neuropsychological approach has established linkages between specific cognitive functions and their associated brain regions. As in the neuroimaging literature, it has become increasingly clear that PFC damage causes profound degradation of reasoning performance. While the PFC has remained an area of strong interest in reasoning, it is also clear that the long term semantic networks constructed from wide-ranging cortical circuits also play a large role in reasoning (Morrison et al., 2004). The effects of cognitive and neurological disorders such as autism, Parkinson's disease, and schizophrenia have also indicated additional brain regions and cognitive components that make up abstract reasoning.

The following sections will review the recent literature describing core cognitive components involved in relational reasoning primarily in healthy and brain-damaged adults. I also focus on the neuroimaging literature and how it has expanded and changed our views of reasoning. Lastly, I will conclude by discussing the future of investigations into reasoning.

2. Relational reasoning

2.1. Abstract relational reasoning

Studies of relational reasoning initially emphasized the contributions of the PFC. Theoretical papers by Robin and Holyoak (1995) and Holyoak and Kroger (1995) postulated that