Neuropsychologia 46 (2008) 2020–2032

NEUROPSYCHOLOGIA

www.elsevier.com/locate/neuropsychologia

Distraction during relational reasoning: The role of prefrontal cortex in interference control

Daniel C. Krawczyk[a,b,*], Robert G. Morrison[c], Indre Viskontas[d], Keith J. Holyoak[e], Tiffany W. Chow[f], Mario F. Mendez[e], Bruce L. Miller[d], Barbara J. Knowlton[e]

[a] The University of Texas at Dallas, United States
[b] University of Texas Southwestern Medical Center at Dallas, United States
[c] Northwestern University, United States
[d] University of California, San Francisco, United States
[e] University of California, Los Angeles, United States
[f] University of Toronto, Canada

Received 18 September 2007; received in revised form 8 December 2007; accepted 1 February 2008
Available online 7 February 2008

Abstract

We compared the reasoning performance of patients with frontal-variant frontotemporal lobar degeneration (FTLD) with that of patients with temporal-variant FTLD and healthy controls. In a picture analogy task with a multiple-choice answer format, frontal-variant FTLD patients performed less accurately than temporal-variant FTLD patients, who in turn performed worse than healthy controls, when semantic and perceptual distractors were present among the answer choices. When the distractor answer choices were eliminated, frontal-variant patients showed relatively greater improvement in performance. Similar patient groups were tested with a relational-pattern reasoning task that included manipulations of one or two relations and both perceptual and semantic extraneous information. Frontal-variant patients showed performance deficits on all tasks relative to the other subject groups, especially when distracted. These results demonstrate that intact prefrontal cortex (PFC) is necessary for controlling interference from perceptual and semantic distractors in order to reason from relational structure.

Keywords: Reasoning; Distraction; Interference; Relational; Control; Attention

1. Introduction

Reasoning requires the coordinated activity of several brain regions. The subprocesses of reasoning include manipulation of information in working memory, formation of transient connections between individual problem elements, and inhibition of inappropriate responses. These cognitive processes are thought to be governed largely by the prefrontal cortex (PFC) (D'Esposito et al., 1995; Fuster, 2000; Smith & Jonides, 1999; Wallis, Anderson, & Miller, 2001).

Patients with frontotemporal lobar degeneration (FTLD) have a form of dementia that causes atrophy to cortical regions within the frontal and temporal lobes (Knibb, Kipps, & Hodges, 2006; Rosen et al., 2002; Snowden, Neary, & Mann, 2007). Onset of cortical atrophy may begin in either the frontal or anterior temporal regions and progress to include both areas, but instances can be found in which cortical damage is restricted to either the frontal or temporal lobes (Chow, Miller, Boone, Mishkin, & Cummings, 2002). In such cases it is possible to dissociate the patient groups based on behavioral and cognitive symptoms and neuroimaging. Frontal and temporal variants of FTLD provide models that can assist us in better characterizing the contributions of the PFC to reasoning performance, and specifically to examine the role of the PFC in control of interference from distracting information during relational reasoning.

Prior studies indicate that frontal-variant FTLD (fvFTLD) leads to reasoning deficits that can be characterized as failures in manipulating and integrating multiple relations in order to solve problems (Waltz et al., 1999). In addition, deficits in interference control also contribute to relational reasoning

* Corresponding author at: Center for BrainHealth®, The University of Texas at Dallas, 2200 Mockingbird Lane, Dallas, TX 75235, United States.
Tel.: +1 972 883 3234; fax: +1 214 905 3026.
E-mail address: daniel.krawczyk@utdallas.edu (D.C. Krawczyk).

0028-3932/$ – see front matter
doi:10.1016/j.neuropsychologia.2008.02.001

impairments in fvFTLD patients (Morrison et al., 2004). Interference control is an important aspect of relational reasoning (see Morrison, Doumas, & Richland, 2006; Morrison et al., 2004; Richland, Morrison, & Holyoak, 2006; Viskontas, Morrison, Holyoak, Hummel, & Knowlton, 2004), as it is necessary to avoid compelling semantic or perceptual matches that compete with matching based on relational structure (Gentner & Toupin, 1986; Holyoak & Koh, 1987; Krawczyk, Holyoak, & Hummel, 2004, 2005; Markman, 1997). While the PFC has historically been considered to be important for inhibitory processes that may underlie interference control (Butter, 1969; Iverson & Mishkin, 1970; Miller & Cohen, 2001; Quintana, Fuster, & Yajeya, 1989; Shimamura, 2000), this function has had relatively little direct investigation in the domain of reasoning. The current investigation specifically tests the extent to which interference control is important for visual reasoning tasks in which suppressing semantically and perceptually related items is essential for accurate performance.

Studies of the neural underpinnings of relational reasoning initially focused on the PFC and its contribution to the ability to coordinate attention and working memory (Holyoak & Kroger, 1995; Robin & Holyoak, 1995). Several of these studies were based on the framework advanced by Halford (e.g. Halford, Wilson, & Phillips, 1998), which quantifies relational complexity of information as the number of variables that must be integrated in order to solve a problem. The relational complexity metric has been applied to reasoning studies in development (e.g. Andrews & Halford, 2002; Birney, Halford, & Andrews, 2006; Richland et al., 2006), aging (Viskontas, Holyoak, & Knowlton, 2006), and chromosomal disorders (Fales et al., 2003).

This approach is exemplified by studies in which PFC-damaged subjects were compared to other subject groups that lacked frontal impairments. Waltz et al. (1999) tested fvFTLD patients on a version of the Raven's progressive matrices (RPM; Raven, 1941), and a transitive inference task. The RPM has been considered to encapsulate many of the skills that comprise fluid intelligence (Duncan et al., 2000; Snow, Kyllonen, & Marshalek, 1984). Notably, this task requires the ability to maintain different pieces of relational information (about changes in different dimensions) and integrate them to form a solution. Findings showed that frontal-damaged groups failed selectively on problem types that required the integration of multiple relations, compared to those problems in which only one relation was required for a correct solution. Similar findings were obtained with frontally impaired Alzheimer's disease patients on matrices problems and relational working memory problems (Waltz et al., 2004).

Recent studies (Morrison et al., 2006; Viskontas et al., 2004) have suggested that developmental and patient differences in relational reasoning as characterized by relational complexity can best be accounted for by variation in inhibitory control, a suggestion consistent with the importance of PFC in relationally complex reasoning. The involvement of the PFC in analogical and relational reasoning studies has received further support from neuroimaging studies. Early studies investigated the neural correlates of variations of the RPM. Prabhakaran, Smith, Desmond, Glover, and Gabrieli (1997) found predominantly PFC and parietal lobe activation in an fMRI study of this task. Similar results have been reported by Christoff et al. (2001) and Kroger et al. (2002), both of whom reported anterior rostrolateral PFC regions to be selectively active for the most complex matrix problems that required integrating across several dimensions. Relational processing has also been shown to activate PFC in neuroimaging studies of geometric and mathematical reasoning (Melrose, Poulin, & Stern, 2007; Prabhakaran, Rypma, & Gabrieli, 2001).

Recent functional neuroimaging studies of analogical reasoning have revealed evidence of further PFC specialization. Across several studies, investigators have reported left-anterior PFC activation that appears to be selective for the relational mapping aspect of analogical reasoning (Bunge, Wendelken, Badre, & Wagner, 2005; Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006; Luo et al., 2003). In one study, Bunge et al. (2005) found both left-anterior and ventrolateral PFC areas to be associated with processing analogies; however, the ventrolateral PFC alone was also sensitive to word association strength, suggesting that this region was more involved in semantic retrieval than relational integration. The other studies also found broad PFC activation in response to processing analogy problems, but the anterior portion of the PFC has been found to be most sensitive specifically to the relational demands of the tasks. This pattern of findings indicates that relational reasoning appears to selectively recruit rostrolateral PFC, but that the process overall involves more of the PFC as well as relevant posterior regions (Wharton et al., 2000). This movement toward separation of function of PFC areas in complex reasoning is consistent with recent theoretical claims that the PFC can be divided into subprocessing regions linked by an anterior control system (Christoff & Owen, 2006; Koechlin, Ody, & Kouneiher, 2003; Koechlin & Summerfield, 2007).

A second important feature of many tasks that are sensitive to frontal impairments is the need to control interference from extraneous information. For example, in the Wisconsin Card Sorting Test the tendency to respond based on a consistent dimension must be suppressed in order to shift response dimensions at the appropriate time. Similar impairments have been shown in both the human and animal literature with reversal learning deficits following PFC damage, in which responses to a previously rewarded stimulus must be suppressed in order to respond correctly to a previously unrewarded stimulus (Butter, 1969; Iverson & Mishkin, 1970; O'Doherty, Kringelbach, Rolls, Hornak, & Andrews, 2001; Rolls, Hornak, Wade, & McGrath, 1994). In a prior study we demonstrated that frontal-variant FTLD patients show a specific deficit in solving two-choice A:B::C:D style verbal analogy problems when a semantic distractor item, closer in association to the C term than the correct D term, was presented as a possible answer choice (Morrison et al., 2004). Furthermore, we showed in a picture analogy task that fvFTLD patients tended to provide many perceptually similar answers, rather than analogical answers, compared to healthy control subjects. This aspect of analogical reasoning has received relatively little direct investigation in PFC-impaired patients.