Neuropsychologia 51 (2013) 713–724

Contents lists available at SciVerse ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Lesions to right prefrontal cortex impair real-world planning through premature commitments

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ARTICLE INFO

Article history:
Received 23 April 2012
Received in revised form
25 October 2012
Accepted 22 November 2012
Available online 22 December 2012

Keywords:
Planning
Right prefrontal cortex

ABSTRACT

While it is well accepted that the left prefrontal cortex plays a critical role in planning and problem-solving tasks, very little is known about the role of the right prefrontal cortex. We addressed this issue by testing five neurological patients with focal lesions to right prefrontal cortex on a real-world travel planning task, and compared their performance with the performance of five neurological patients with focal lesions to left prefrontal cortex, five neurological patients with posterior lesions, and five normal controls. Only patients with lesions to right prefrontal cortex generated substandard solutions compared to normal controls. Examination of the underlying cognitive processes and strategies revealed that patients with lesions to right prefrontal cortex approached the task at an excessively precise, concrete level compared to normal controls, and very early locked themselves into substandard solutions relative to the comparison group. In contrast, the behavior of normal controls was characterized by a judicious interplay of concrete and abstract levels/modes of representations. We suggest that damage to the right prefrontal system impairs the encoding and processing of more abstract and vague representations that facilitate lateral transformations, resulting in premature commitment to precise concrete patterns, and hasty albeit substandard conclusions (because the space of possibilities has not been properly explored).

1. Introduction

The role of the prefrontal cortex in planning processes has been highlighted by several researchers in both patients with focal lesions (Bechara, Damasio, Damasio, & Anderson, 1994; Burgess, 2000; Colvin, Dunbar, & Grafman, 2001; Fellows, 2006; Goel & Grafman, 2000; Goel, Grafman, Tajik, Gana, & Danto, 1997; Miotto & Morris, 1998; Penfield & Evans, 1935; Shallice, 1982) and closed head injury (Bamdad, Ryan, & Warden, 2003; Dritschel, Kogan, Burton, Burton, & Goddard, 1998; Fortin, Godbout, & Braun, 2002, 2003; Shallice & Burgess, 1991a). These studies have confirmed that frontal lobe patients (1) are impaired in planning tasks; (2) exhibit differences, compared to normal controls, in both the ability to formulate and to execute plans (Chevignard et al., 2000); and (3) in terms of plan formulation, the difficulties seem to be more at the "global" or "macro" level (that is, at the level of minutes) than the "local" or "micro" level (at the level of seconds) (Fortin et al., 2003; Goel et al., 1997). However, existing studies have not adequately addressed hemisphere specific involvement of prefrontal cortex.

The idea that the left hemisphere is involved (or even dominant) in the critical domains of higher-level thinking processes has been advanced by the split brain patient literature (Gazzaniga, 2000; Gazzaniga 1998). This same literature limits the role of the right hemisphere, and in particular the right PFC, to little more than organization of visual information (Corballis, 2003).

However, this conclusion is much less certain in the context of the broader neuropsychological literature. Four of the above studies (Colvin et al., 2001; Fellows, 2006; Miotto & Morris, 1998; and Shallice, 1982) have specifically grouped patients into left and right hemisphere lesions. These studies report either no difference in the performance of patients with lesions to left or

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0028-3932/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.neuropsychologia.2012.11.029

right hemisphere (Colvin et al., 2001; Fellows, 2006; Miotto & Morris, 1998), or that the left hemisphere patients do worse than the right hemisphere patients (Shallice, 1982).

A recent review on neuroimaging studies of the popular Tower of London (ToL) planning task (Kaller, Rahm, Spreer, Weiller, & Unterrainer, 2011) noted that, of the 24 imaging studies reporting dorsal lateral PFC activation, 6 report posterior left dorsolateral PFC activation, 3 report right dorsal lateral PFC activation, while 15 report bilateral activation. These data would seem to suggest minimal lateralization of function in PFC, at least as far as planning was concerned. However, planning is a complex, multi-faceted, multi-step task. So another possibility is that the mixed results in the literature are a function of the particular planning steps/functions that a study emphasizes and measures. Indeed, many studies have viewed planning as a unitary construct and not differentiated between individual steps. Kaller et al. (2011) provide a nice neuropsychological demonstration of this in the context of ToL task. In differentiating between different planning steps they find a double dissociation between "goal hierarchy" (the amount of variability/flexibility in a sequence of steps) and "search depth" (looking past intermittent steps or subgoals), with the former activating left dorsolateral PFC and the latter activating right dorsal lateral PFC.

Such dissociations are in keeping with results in the logical reasoning literature that indicate left PFC dominance in logical reasoning (Goel, 2007; Prado, Chadha, & Booth, 2011), but with a critical role for the right PFC in the resolution of conflict (Goel & Dolan, 2003), dealing with unfamiliar content (Goel, Buchel, Frith, & Dolan, 2000), and resolving indeterminate inferences (Goel et al., 2007). Similarly, in the context of problem solving, data suggest that right PFC plays a selective but critical role in situations where problem spaces become underspecified or involve mental set shifts. For example, broadening the search space on scrambled word tasks by broadening semantic categories lexical strings can belong to (e.g., make the word 'knife' with IKFEN; make a word for a kitchen utensil with IKFEN; make a word with IKFEN) reduces task constraints and selectively engages right prefrontal cortex (Vartanian & Goel, 2005). Hypothesis generation tasks, like the Matchstick problems, that involve mental set shifts to overcome implicit misleading cues selectively activate right prefrontal cortex in the misleading condition (Goel & Vartanian, 2005; Reverberi, Lavaroni, Gigli, Skrap, & Shallice, 2005).

It has been noted that there are important differences between the problems administered as part of neuropsychological test batteries and real-world problems encountered in daily life (Bechara et al., 1994; Goel et al., 1997; Shallice & Burgess, 1991b). It has been further argued that one critical difference has to do with the structure of the problem space (Goel, 2010; Goel et al., 1997). Most problem used in the neuropsychological literature are in some important respects a small, special subset of real-world tasks (often called well-structured tasks), characterized by completely specified start states, goal states, and transformation functions (among other things) (Goel, 1995; Reitman, 1964). Classic examples of such tasks are the Tower of Hanoi and Tower of London tasks used to measure executive functions. By contrast, the larger class of real-world problems have a very broad and poorly constrained and defined problem space. This larger problem set, exclusive of the well-structured set, has been referred to as ill-structured.

Goel (2010) has argued that one possible factor in the differential involvement of left and right PFC in different types of problem solving tasks may be the structure of the underlying mental (and external) representations and transformations required by the tasks. The well-structured subset of problems require precise, concrete representations for successful solution while ill-structured problems require more abstract, ambiguous, and vague mental representations for solution (at least initially). In the context of real-world planning problems, which have both ill and well-structured components, the full range of cognitive resources is required.

Real-world problems begin as ill-structured problems and go to become more well-structured as solutions emerge. More specifically, real-world problem solving typically involves four phases: *problem scoping*, *preliminary solutions*, *refinement*, and *detailing* of solutions. Each phase differs with respect to the type of information dealt with, the degree of commitment to generated ideas, the level of detail attended to, the number and types of transformations engaged in, and the mental representations needed to support the different types of information and transformations (Goel, 1995). As one progresses from the preliminary phases to the detailing phases, the problem becomes more structured. This is depicted in Fig. 1.

Problem scoping is the process of bringing background experience and knowledge to understand the problem statement. *Preliminary solution generation* is a classical case of creative, ill-structured problem solving. It is a phase of "cognitive way-finding", a phase of concept construction, where a few kernel ideas are generated and explored through transformations. This generation and exploration of ideas/concepts is facilitated by the *abstract* nature of information being considered, a low degree of commitment to generated ideas, the coarseness of detail, and a large number of *lateral transformations*. A lateral transformation is one where movement is from one idea to a slightly different idea rather than a more detailed version of the same idea. Lateral transformations are necessary for the *widening* of the problem

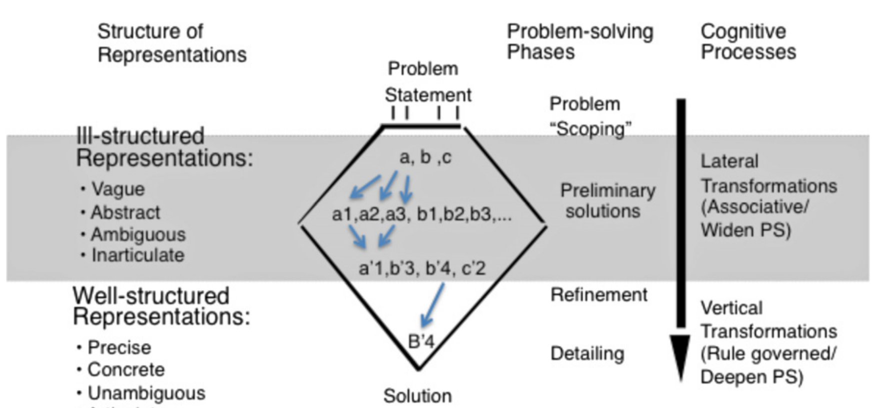

Fig. 1. The state space for real-world problems must support the different problem solving phases, which in turn require different representational systems and cognitive processes.