Brain & Language 164 (2017) 16–24

Contents lists available at ScienceDirect

Brain & Language

journal homepage: www.elsevier.com/locate/b&l

Short communication

Bilateral parietal contributions to spatial language

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ARTICLE INFO

Article history:
Received 7 December 2015
Revised 7 September 2016
Accepted 12 September 2016
Available online 28 September 2016

Keywords:
Spatial language
Parietal lobe
Precuneus
Laterality
fMRI

ABSTRACT

It is commonly held that language is largely lateralized to the left hemisphere in most individuals, whereas spatial processing is associated with right hemisphere regions. In recent years, a number of neuroimaging studies have yielded conflicting results regarding the role of language and spatial processing areas in processing language about space (e.g., Carpenter, Just, Keller, Eddy, & Thulborn, 1999; Damasio et al., 2001). In the present study, we used sparse scanning event-related functional magnetic resonance imaging (fMRI) to investigate the neural correlates of spatial language, that is; language used to communicate the spatial relationship of one object to another. During scanning, participants listened to sentences about object relationships that were either spatial or non-spatial in nature (color or size relationships). Sentences describing spatial relationships elicited more activation in the superior parietal lobule and precuneus *bilaterally* in comparison to sentences describing size or color relationships. Activation of the precuneus suggests that spatial sentences elicit spatial-mental imagery, while the activation of the SPL suggests sentences containing spatial language involve integration of two distinct sets of information – linguistic and spatial.

1. Introduction

Many aspects of language processing are localized to the left hemisphere in the majority of people, as originally suggested by Dax (1865) and later by Paul Broca in 1865 (Broca, 1865; Manning & Thomas-Antérion, 2011). Conversely, spatial processing is primarily localized to the right hemisphere (Witelson, 1976). These observations were originally established on the basis of patient studies showing consistent links between language impairments and left hemisphere damage, particularly in specific frontal and temporal regions, and between impaired spatial processing and right hemisphere damage (e.g., Dronkers, Redfern, & Knight, 2000; Karnath, Berger, Küker, & Rorden, 2004). More recently, this distinction has been further corroborated by brain imaging studies using different techniques, such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI), transcranial magnetic stimulation, and functional transcranial Doppler sonography (e.g., Duecker, Formisano, & Sack, 2013; Gutierrez-Sigut, Payne, & MacSweeney, 2015; Richardson, Fillmore, Rorden, Lapointe, & Fridriksson, 2012).

Although the neural circuits underlying the two types of processes are likely distinct, linguistic and spatial processing must interface to some degree, as in the case of "spatial language," which allows language users to communicate about the location of objects (Chatterjee, 2001). Although different languages encode spatial relations in slightly different ways, spatial language is generally characterized by a systematic schematization of space and the use of one region (the "ground") to describe the location of another (the "figure"; Bowerman, 1996; Levinson, 2003; Talmy, 2000). In many languages, this spatial language hinges on a small set of closed-class words (Landau & Jackendoff, 1993). For example, in English, spatial descriptions involve a relatively small number of prepositions (*in*, *on*, etc.) used to describe the location of a figure in terms of its spatial relation to a ground (e.g., *the bird [figure] is in the tree [ground].*) The universal properties of the language of space suggests that this aspect is unique within language, but its relation to general spatial processing in the brain remains unclear. Does

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http://dx.doi.org/10.1016/j.bandl.2016.09.007

this type of language processing involve neural circuitry that is shared by more general nonlinguistic spatial processing? The research we report here aims to address this question by examining the neural basis of the language of space. Before describing our research in detail, we provide a short review of the existing literature.

1.1. Brain bases of spatial language

Landau and Jackendoff (1993) proposed that the schematization found in spatial language reflects the properties of the underlying neural circuits. Building upon evidence for the existence of separate dorsal and ventral pathways in the visual system (e.g., Ungerleider & Haxby, 1994; Ungerleider & Mishkin, 1982), Landau and Jackendoff theorized that processing spatial language engages the dorsal visual pathway, which is important for identifying the location of objects (the "where" system), whereas object descriptions and identification engage the ventral system, which is important for object recognition (the "what" system). In line with this prediction, a number of neuroimaging studies found evidence for the involvement of the parietal lobe in processing spatial language (e.g., Carpenter, Just, Keller, Eddy, & Thulborn, 1999; Damasio et al., 2001; Emmorey et al., 2005; Noordzij, Neggers, Ramsay, & Postma, 2008; Wallentin, Weed, Østergaard, Mouridsen, & Roepstorff, 2008). Damasio et al. (2001) showed that naming spatial relationships compared to object naming evoked activity in the left inferior parietal lobe. Interestingly, when the spatial relation task was compared to a control task involving normal or inverted faces, which also contains a spatial component, differences in activation were found only in left frontal and temporal regions, but not in any parietal regions. This further supports the role of the left parietal regions in spatial processing and spatial language.

A series of patient studies by Kemmerer and Tranel further supports the role of left parietal regions in spatial language (Kemmerer & Tranel, 2003; Tranel & Kemmerer, 2004). Kemmerer and Tranel (2003) found a double dissociation: damage to the left frontal operculum was associated with deficits in understanding action verbs, whereas damage to the left inferior and superior parietal regions was associated with deficits in understanding locative prepositions. In a follow-up study, Tranel and Kemmerer (2004) examined six patients who showed pervasive deficits in processing spatial language and found that these deficits were associated with damage to the posterior left front operculum, inferior left parietal operculum, and the underlying white matter. Together, these results provide further support for the involvement of left parietal and frontal regions as well as the connective path between them in spatial language processing.

While the evidence reviewed so far suggests that spatial language is left lateralized, other evidence might be taken to suggest bilateral involvement. An early study on language comprehension using fMRI found that comparing spatial descriptions (a linguistic task component) to spatial configurations of objects (a visuospatial task component) was associated with increased activity in the posterior left temporal gyrus but also in visuospatial parietal areas *bilaterally* (Carpenter et al., 1999). However, given the nature of the picture comparison task, the bilateral parietal involvement may be more explicitly related to visuospatial *processing*, as opposed to spatial *language* per se. Wallentin, Østergaard, Lund, Østergaard, and Roepstorff (2005) similarly found bilateral frontal and parietal activity associated with the processing of sentences describing movement towards concrete spatial locations (e.g., *into the labyrinth*), while movement towards abstract locations (e.g., *into madness*) evoked more left-lateralized activity. Examining the BOLD activation associated with answering spatial vs. non-spatial recall questions about the figures in a previously viewed scene, Wallentin, Roepstorff, Glover, and Burgess (2006) found that recalling spatial information led to bilateral activation of the precuneus, and Wallentin et al. (2008) found a very similar finding when participants comprehended descriptions of scenes presented via headphones. Thus, while there is consistent evidence for lateralization of spatial processing to the right hemisphere and language processing to the left hemisphere, there is little consensus as to whether or not spatial language processing is predominantly uni- or bi-lateral.

While the language of space in spoken languages is largely schematic (Landau & Jackendoff, 1993), sign languages, perhaps as a function of their use of the visuospatial medium, employ much richer spatial language that is capable of expressing spatial relations in great accuracy. Comparing the neural activation of individuals fluent in both English and American Sign Language (ASL) using PET, Emmorey et al. (2005) found significant bilateral activation of the parietal cortex during production of spatial language, regardless of whether this production was in English or ASL; however, greater activation of the right parietal cortex was associated with production in ASL. This greater activation may, in part, be due to the visual-to-motoric transformation of language that is necessary in ASL production (Emmorey et al., 2005). However, this difference in parietal recruitment between the two languages may also reflect an asymmetry between the right and left parietal lobes, with the right parietal lobe possibly specializing in precise spatial coordinates and the left in categorical spatial relations (Castelli, Glaser, & Butterworth, 2006; Kemmerer & Tranel, 2000; Kosslyn, Sokolov, & Chen, 1989). Notably, ASL has two alternative spatial constructions: classifier predicates, in which detailed spatial relationships can be communicated, and prepositions, a closed class of words similar to English prepositions in that they only express categorical spatial relations (Emmorey et al., 2002). Neuroanatomically, these two constructions are quite distinct, with the classifier constructions employing bilateral parietal regions, and the ASL prepositions more left lateralized (Emmorey et al., 2002). Thus, the inherently spatial medium used by sign language appears to allow for the usage of a precise coordinate system in the right parietal lobe for certain types of spatial descriptions, whereas spoken English spatial descriptions and ASL spatial prepositions recruit the left categorical system (Emmorey et al., 2002, 2005).

In summary, although the question of whether spatial language processing is left lateralized or bilateral is of theoretical importance in that it can inform the understanding of hemispheric specialization, previous results are inconsistent. One goal of the present research is to test whether processing spoken English spatial description is bilateral or dominantly left lateralized.

1.2. Regions of the parietal lobe in spatial language

Although most studies of spatial language have implicated the parietal regions, there is little agreement about which specific parietal areas are involved. Implicated areas include the parietal lobule as a whole, the supramarginal gyrus, the intraparietal sulcus, the superior parietal lobule (SPL) and the precuneus (e.g., Carpenter et al., 1999; Damasio et al., 2001; Emmorey et al., 2002, 2005; Kemmerer & Tranel, 2003; Wallentin et al., 2005, 2006, 2008). In particular, the supramarginal gyrus (SMG) has been implicated in many studies, though only in the left hemisphere (Damasio et al., 2001; Emmorey et al., 2002, 2005; Kemmerer & Tranel, 2000; Tranel & Kemmerer, 2004). Carpenter et al. (1999) and Emmorey et al. (2005) also found activation of the right SMG and right precuneus. Wallentin et al. (2005, 2006, 2008) also found bilateral activation of the precuneus across three very different types of spatial linguistic tasks.

There are a number of possible reasons for the inconsistencies seen across neuroimaging studies of spatial language. First, the