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Naming and gesturing spatial relations: Evidence from focal brain-injured individuals

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ABSTRACT

Spatial language helps us to encode relations between objects and organize our thinking. Little is known about the neural instantiations of spatial language. Using voxel-lesion symptom mapping (VLSM), we tested the hypothesis that focal brain injured patients who had damage to left frontal–parietal peri-Sylvian regions would have difficulty in naming spatial relations between objects. We also investigated the relationship between impaired verbalization of spatial relations and spontaneous gesture production. Patients with left or right hemisphere damage and elderly control participants were asked to name static (e.g., an apple *on* a book) and dynamic (e.g., a pen *moves over* a box) locative relations depicted in brief video clips. The correct use of prepositions in each task and gestures that represent the spatial relations were coded. Damage to the left posterior middle frontal gyrus, the left inferior frontal gyrus, and the left anterior superior temporal gyrus were related to impairment in naming spatial relations. Production of spatial gestures negatively correlated with naming accuracy, suggesting that gestures might help or compensate for difficulty with lexical access. Additional analyses suggested that left hemisphere patients who had damage to the left posterior middle frontal gyrus and the left inferior frontal gyrus gestured less than expected, if gestures are used to compensate for impairments in retrieving prepositions.

1. Introduction

Spatial language, such as words for locative relations and actions, helps us to encode spatial information in the environment and organize our thinking (Chatterjee, 2001, 2008). Despite its significance in framing our thinking, few studies have investigated the neural underpinnings of spatial language (Amorapanth, Widick, & Chatterjee, 2009; Chatterjee, 2008; Damasio, Grabowski, Tranel, Ponto, Hichwa, & Damasio, 2001; Kemmerer, 2006). The current study is motivated by the hypothesis that perceptual and lexical-semantic spatial information have a parallel organization in the brain. Based on the putative neural organization of the perception of locative relations we predict that patients with focal brain injury to the left frontal–parietal peri-Sylvian regions would have difficulty in naming spatial relations between objects.

People gesture spontaneously when they speak. Virtually nothing about the spontaneous use of spatial gestures in the setting of neurological disease is known. It is possible that people rely on spontaneous gestures when they have difficulty communicating verbally. We see this behavior commonly among travelers who use gestures when they try to communicate with people with whom they do not share a language. Alternatively, deficits in expressing spatial relations verbally might generalize to deficits in expressing spatial relations gesturally. In this study, we will also explore these possible consequences of focal brain injury on the production of spontaneous spatial gestures.

Spatial language comprises terms for a range of spatial relations. Here, we focus on locative prepositions, which describe spatial relations between a *figure* (the object to be located) and its *ground* (the reference object) (Talmy, 1983). For example, in the sentence "the book is on the shelf," the book refers to the figure and the shelf refers to the ground. The preposition "on" presents the spatial relationship between the figure and ground. Thus, locative prepositions describe "extrinsic relations" in which an object (figure) is related to an external referent (ground) (Chatterjee, 2008). In the following sections, we first review our current understanding of the neural basis of locative information. We then discuss the relation between speech and gesture and how gesture might compensate for impaired speech before presenting the current study.

1.1. The neural correlates of locative prepositions

The presumed neural correlates of the perception of spatial relations follow from a fundamental tenet of visual neuroscience

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(Ungerleider & Mishkin, 1982), which is that visual processing segregates into two pathways. The ventral stream ('what' pathway) processes information about object properties, such as color, shape or size of an object. The dorsal stream ('where' pathway) processes spatial information such as the location and motion of an object. Even though these pathways interact, studies from nonhuman primates (e.g., Orban, Van Essen, & Vanduffel, 2004; Wang, Tanaka, & Tanifuji, 1996) and human adults (e.g., Bly & Kosslyn, 1997; Haxby et al., 1991) support this division of labor in visual processing.

Consistent with this two-stream hypothesis, brain damage to fronto-parietal circuits can produce profound spatial deficits such as spatial neglect and simultanagnosia. Germane to our investigation, both fMRI studies in healthy participants and behavioral studies in patients with focal brain damage confirm a fronto-parietal circuit for knowledge of locative relations (e.g., Amorapanth et al., 2009; Wu, Waller, & Chatterjee, 2007). The intraparietal sulcus and the posterior middle frontal gyrus seem to be critical nodes mediating this knowledge.

We previously proposed that spatial perception and language have a parallel organizational structure within the brain (Chatterjee, 2008). For example, the perception of actions relies on posterior temporal-occipital regions including area MT/MST and the lexical expression of these actions (action verbs) activates areas just anterior and dorsal to this area (Kable, Kan, Wilson, Thompson-Schill, & Chatterjee 2005). The general hypothesis is that there is a perceptual to verbal gradient organized within the left hemisphere of right-handed individuals, such that perceptual nodes serve as points of entry for their lexical counterparts that are shifted centripetally towards peri-Sylvian cortex (Chatterjee, 2008). As suggested by Kemmerer (2010), the areas related to lexical-semantic encoding of spatial relations can be close to, but distinguishable from the representation of spatial relation dedicated to perception.

Recent empirical findings support this parallel organization of spatial perception and language (e.g., Amorapanth et al., 2009, 2012; Baciu, Koenig, Vernier, Bedoin, Rubin, & Segebarth, 1999; Damasio et al., 2001; Emmorey et al., 2002; Kemmerer, 2006; Noordzij, Neggers, Ramsey, & Postma, 2008; Tranel & Kemmerer, 2004; Wu et al., 2007). For example, Tranel and Kemmerer (2004) examined brain-injured patients' knowledge of locative prepositions. Participants were presented groups of three pictures. Each set had two objects and involved 12 different spatial relations. Then they were asked to point to the picture that involved a different categorical spatial relation than the other two. They found that damage to the white matter underlying the left supramarginal gyrus and frontal operculum were associated with deficits in matching these spatial relations (see also Kemmerer & Tranel, 2000). Amorapanth et al. (2009) extended these findings and found that damage to the left supramarginal gyrus and angular gyrus, the left posterior middle and inferior frontal gyri, and the left superior temporal gyrus were associated with deficits in matching the categorical spatial relations (see also Amorapanth et al., 2012; Wu et al., 2007). Neuroimaging studies corroborate these findings (Amorapanth et al., 2009; Baciu et al., 1999; Noordzij et al., 2008).

The growing literature on the neural basis of locative prepositions has focused on comprehension. Only a few studies have investigated the neural underpinnings of *producing* locative prepositions. These studies demonstrated that the neural organization of lexical and semantic organization of spatial language might be similar to perceiving spatial relations (Damasio et al., 2001; Emmorey et al., 2002; Kemmerer, 2006; MacSweeney et al., 2002; Tranel, Manzel, Asp, & Kemmerer, 2008). For example, Damasio et al. (2001) using PET imaging found that naming static spatial relations between objects from drawings, activated the left supramarginal gyrus, the inferior prefrontal cortex, left inferior temporal lobe, and right parietal regions. Case studies with aphasic patients show similar patterns of neural involvement in producing locative prepositions (e.g., Friederici, 1982; Kemmerer & Tranel, 2000; Tesak & Hummer, 1994; Tranel & Kemmerer, 2004).

Here we examine focal brain injured patients' production of locative prepositions using voxel-lesion symptom mapping (VLSM) analysis. VLSM is a powerful technique to examine brain–behavior relationships in patients with focal brain injury (Bates et al., 2003; Kimberg, Coslett, & Schwartz, 2007). Unlike traditional lesion mapping methods, in VLSM patients are not classified based on lesion site, clinical diagnosis or behavioral performance. One need not make categorical distinctions about whether a patient has a deficit or not, since performance on tasks are treated as continuous variables. VLSM offers specificity to lesion analysis by increasing the possibility of detecting neuroanatomical regions underlying a cognitive process that might be missed in coarser traditional lesion mapping methods. Furthermore the inferential strengths of lesion methods offer an important constraint on neural hypotheses generated by functional neuroimaging methods (Chatterjee, 2005; Fellows, Heberlein, Morales, Shivde, Waller, & Wu, 2005).

Our focus on production of locative information raises additional questions about alternate means of communication, such as the use of gestures. Do gestures simply accompany speech? Do they help to compensate when verbal communication is impaired or are they also impaired? In the next section, we briefly review the interactions between speech and gesture to motivate our investigations of the relationship of spontaneous gesture and impaired speech.

1.2. Associations between speech and gesture

People gesture spontaneously when they talk. The hand movements of co-speech gestures are typically related to the accompanying language by their form and function. Gestures can be classified into four main categories—*deictic gestures* (i.e., pointing to an object, person, or location), *beat gestures* (i.e., quick hand movements highlighting the prosody of the speech without semantic meaning), and *iconic gestures* that represent objects, events such as moving the hand in an arc to refer to direction of an action or *metaphoric gestures* that refer to abstract ideas (McNeill, 1992). In this paper, we only examine iconic gestures as relevant to the communication of spatial information.

McNeill (1992) claims that speech and gesture are complementary processes that form a tightly integrated language system (also see Alibali, Kita, & Young, 2000; Feyereisen, 1983; Goldin-Meadow, 2003; Kita & Özyürek, 2003; McNeill, 2005). Without speech, many iconic gestures might not have an obvious meaning. But in combination with speech, gestures can clarify or emphasize spatial aspects of the propositional content of speech. Despite considerable behavioral evidence of a close relationship between speech and gesture, we know relatively little about the neural correlates of co-speech gestures (Holle, Gunter, Rueschemeyer, Hennenlotter, & Iacoboni, 2008; Skipper, Goldin-Meadow, Nusbaum, & Small, 2007; Willems, Özyürek, & Hagoort, 2007; for a review see Willems & Hagoort (2007). For example, Willems et al. (2007) reported that co-speech gestures and language processing recruit overlapping areas in the left inferior frontal gyrus (BA 45), suggesting a pivotal role of Broca's area in processing both types of information (but see Skipper et al., 2007).

Most research on the neural correlates of co-speech gesture production has focused on patients with aphasia (e.g., Ahlsén, 1991; Béland & Ska, 1992; Cicone, Wapner, Foldi, Zurif, & Gardner 1979; Cocks, Dipper, Middleton, & Morgan, 2011; Cocks, Sautin, Kita, Morgan, & Zlotowitz, 2009; Dipper, Cocks, Rowe, & Morgan; 2011; Feyereisen, 1983; Friederici, 1981, 1982; Glosser, Wiener, &