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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, &

Kaplan, 1986; Hadar, Burstein, Krauss, & Soroker, 1998; Kemmerer, Chandrasekaran, & Tranel, 2007; Le May, David, & Thomas 1988), patients with Parkinson's disease (e.g., Cleary, Poliakoff, Galpin, Dick, & Holler, 2011), or split-brain patients (e.g., Lausberg, Kita, Zaidel, & Ptito, 2003; Kita & Lausberg, 2008). These studies try to determine whether or not gestures compensate for impaired speech. Some studies suggest that speech impairment is associated with gesture impairment (e.g., Cicone et al., 1979; Glosser et al., 1986; McNeill, 1985). Others indicate that aphasic patients use more iconic gestures than healthy controls (e.g., Feyereisen, 1983; Hadar et al., 1998; Kemmerer et al., 2007; Lanyon & Rose, 2009; Le May et al., 1988). In an early study, Feyereisen (1983) showed that even though Broca's aphasics gesture less per minute compared to healthy controls, they used co-speech gestures per word more often than controls. Hermann, Reichle, Lucius-Hoene, Wallesch, and Johannsen-Horbach (1988) also reported that severely aphasic patients communicated more frequently using nonverbal means such as iconic gestures than healthy controls. These findings support other behavioral studies with healthy patients, which suggest that gesture help with lexical access (Hadar & Butterworth, 1997).

Studies also demonstrate that type and severity of aphasia and the other neuropsychological deficits patients produce variations in gesture production (e.g., Ahlsén, 1991; Béland & Ska, 1992; Cicone et al., 1979; Duffy & Duffy, 1981; Duffy, Duffy, & Pearson, 1975; Glosser et al., 1986; Hermann et al., 1988). For example, Ahlsén (1991) showed that a Wernicke's aphasic used compensatory body communications to overcome speech problems. When comparing Broca's aphasics and Wernicke's aphasics, Le May et al. (1988) found that Wernicke's aphasics produced many kinetographic gestures (i.e., dynamic movement of the hand to represent for example the action of slicing) whereas Broca's aphasics significantly gestured more overall than Wernicke's aphasics and controls.

Other studies focused on how damage to the right hemisphere is associated with gesture production (e.g., Cocks et al., 2007; Hadar & Krauss, 1999; Hadar et al., 1998; Kita & Lausberg, 2008; Lausberg, Zaidel, Cruz, & Ptito 2007; McNeill & Pedelty, 1995). For example, McNeill and Pedelty (1995) suggested that damage to the right hemisphere led to a reduction in the use of gestures because of an impairment in visuo-spatial imagery. Yet, a recent study by Cocks et al. (2007) found that the right hemisphere patients varied in their use of gestures based on the nature of their discourse. In particular, discourse samples with high emotional content resulted in less gesture production than in other discourse types.

Although these neuropsychological studies are informative, the inferences drawn about the relationship between speech and spontaneous gesture, and their neural correlates are drawn from case studies and small series. They typically tally the total number of gestures rather than analyze the specific content of gestures, thus attenuating the relationship between impaired speech and spontaneous gesture.

### 1.3. Summary and predictions

The aims of our study are twofold. We examine (1) the contribution of frontal–parietal peri-Sylvian regions ('where' pathway) to naming locative prepositions by testing focal brain injured patients and (2) the relationship of impaired naming of spatial relations to spontaneous gesture production in these patients.

In this study we use VLSM analysis to test the naming of locative relations in a relatively large sample size of left hemisphere damaged (LHD) and right hemisphere damaged (RHD) patients. We predict that LHD patients who have damage in the peri-Sylvian fronto-parietal regions will be impaired in correctly naming spatial relations between objects.

We also varied the way spatial relations were displayed. Most studies use static pictures as stimuli for presenting the spatial relations (e.g., Damasio et al., 2001; Emmorey et al., 2002). A recent study by Tranel et al. (2008) investigate the influence of static vs. dynamic stimuli on naming actions. They found overlapping neuroanatomical correlates involved in naming both types of stimuli. Moreover, using dynamic stimuli Wu, Morganti, and Chatterjee (2008) showed that attention to 'where' an object moves in space (i.e., dynamic prepositions) activated bilateral parietal and frontal areas as is reported in the processing of locative prepositions. Even though these findings suggest that spatial relations are treated similarly in the brain regardless of whether they are static or dynamic contexts, in this study we will directly compare naming of these two types of spatial relations.

Lastly, we probe the relationship between speech deficits and spontaneous gestures. Patients who have difficulty in naming spatial relations might use iconic spatial gestures to compensate for their impairments. Alternatively, in some aphasic patients (Cicone et al., 1979; McNeill, 1985) gesture production might also be impaired and these patients would not use spatial gestures to compensate for their speech deficits. In these patients the naming deficit reflect deficits at a conceptual level or deficits in both speech and limb motor production systems.

## 2. Materials and methods

### 2.1. Participants

Thirty-two patients with chronic unilateral lesions (16 LHD and 16 RHD patients) were recruited from the Focal Lesion Subject Database at the University of Pennsylvania (Fellows, Stark, Berg, & Chatterjee, 2008). Patients were not chosen based on specific lesion locations or behavioral criteria. The database excludes patients with a history of other neurological disorders, psychiatric disorders, or substance abuse. LHD patients ranged in age from 37 to 79 ($M=64.69$, $SD=11.49$, 10 females) and RHD patients ranged in age from 45 to 87 ($M=63.50$, $SD=11.99$, 11 females). The LHD and patients had an average of 13.6 ($SD=2.02$) and 15.1 ($SD=3.44$) years of education, respectively. Thirteen age-matched (range: 38–77, $M=60.85$, $SD=11.05$, 9 females) and education-matched ($M=16$, $SD=2.12$) older adults served as a healthy control (HC) group. The three groups did not differ in age or years of education, $ps > 0.05$. In addition, LHD and RHD patients did not differ in lesion size, $p > 0.05$. Fig. 1 displays lesion overlap maps of patients. All participants were right-handed, native English-speakers, and provided written, informed consent in accordance with the policies of the University of Pennsylvania's Institutional Review Board. Participants received $15/h for volunteering their time. Table 1 presents the detailed demographic data for each patient.

### 2.2. Tasks and stimuli

#### 2.2.1. Neuropsychological tasks

Patients were administered the language comprehension and language production subtests of the Western Aphasia Battery (WAB; Kertesz, 1982). The scores from these neuropsychological tasks are presented in Table 1. They were also administered the Object and Action Naming Battery (OANB; Druks, 2000). In this task, each patient named 50 pictures of actions and 81 pictures of objects.

#### 2.2.2. Experimental tasks

Two experimental tasks, consisting of static pictures and dynamic movie clips of different spatial relations between two objects were created. The *static spatial relations task* had 24 pictures depicting four different spatial relations, two topologic (*in, on*) and two projective (*above, below*) relations between two objects. A male's hand illustrated the spatial relation in each picture. The pictures were taken with a Sony digital camera on a white table (see Fig. 2A for sample stimulus). The final set of 24 was selected from 36 pictures based on ratings of familiarity and naming of the spatial relations by 18 native English speakers with a mean age of 21.88 (range: 18–27, $SD=2.76$). After seeing each picture, individuals first rated the familiarity of the objects in the picture on a 5-point scale (1=not familiar at all, 5=very familiar). Then, they named the spatial relation between two objects. To ensure that participants used both *above* and *below* in their descriptions of the spatial relations, the experimenter started the sentences that the participants were asked to complete. For example, when the participants saw the picture of a cup on a book, they first rated the familiarity of two objects by simply hitting 1–5 on the keyboard. Then, the experimenter said "The cup…" and the participant finished the sentence by saying "The cup is on the book." Two practice trials were presented before the start of the task. Stimuli were presented on a

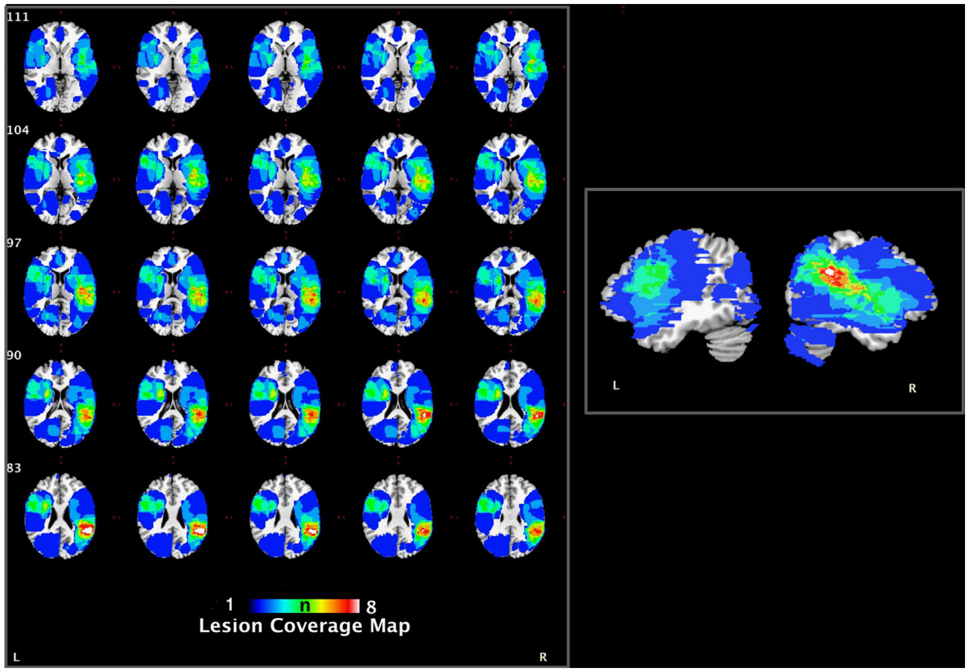


**Fig. 1.** Coverage map indicating the lesion locations for all participants. The colored scale represents the number of lesions for each pixel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 1**
Patient demographic and neuropsychological data.

| Patient | Gender | Age | Education (years) | Lesion side | Location | Lesion size (# of voxels) | Cause | Chronicity (months) | WAB (AQ) | OANB (action) | OANB (object) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| LT_85 | F | 63 | 15 | L | I | 13,079 | Stroke | 177 | – | – | – |
| CD_141 | F | 52 | 16 | L | Pe | 21,605 | Stroke | 143 | 98.8 | 100 | 96 |
| KG_215 | M | 61 | 14 | L | F | 17,422 | Stroke | 145 | 94.4 | 96 | 93.8 |
| TO_221 | F | 77 | 13 | L | O | 5886 | Stroke | 160 | 100 | 100 | 100 |
| BC_236 | M | 65 | 18 | L | FP | 155,982 | Stroke | 210 | 90.8 | 88 | 94 |
| XK_342 | F | 57 | 12 | L | OT | 42,144 | Stroke | 125 | 93.4 | 94 | 93 |
| TD_360 | M | 58 | 12 | L | T BG | 38,063 | Stroke | 118 | 65.3 | 52 | – |
| IG_363 | M | 74 | 16 | L | F | 16,845 | Stroke | 117 | 91.4 | 96 | 95 |
| KD_493 | M | 68 | 14 | L | ACA | 22,404 | Aneurysm | 101 | 92.1 | 98 | 95 |
| DR_529 | F | 66 | 12 | L | PA F | 8969 | Stroke | 100 | – | – | – |
| DR_565 | F | 53 | 12 | L | PA F | 14,517 | Aneurysm | 103 | 99.8 | 98 | 97.5 |
| MC_577 | F | 79 | 11 | L | C | 4191 | Stroke | 50 | 85.3 | 82 | 79 |
| NS_604 | F | 37 | 12 | L | PO | 79,231 | AVM | 113 | – | 100 | 98 |
| UD_618 | M | 77 | 15 | L | F | 48,743 | Stroke | 47 | 93.6 | 76 | 85 |
| KM_642 | M | 77 | 12 | L | P | 7996 | Stroke | 109 | 96.8 | 94 | 98 |
| FC_83 | M | 70 | 12 | R | FTP | 8040 | Stroke | 169 | 99.8 | 96 | 98 |
| MB_101 | F | 58 | 18 | R | T BG | 10,543 | Stroke | 426 | 98.4 | 98 | 98 |
| NC_112 | F | 48 | 16 | R | O | 4733 | Stroke | 178 | 100 | 98 | – |
| RT_309 | F | 66 | 21 | R | T | 79,691 | Hematoma | 128 | – | – | – |
| DF_316 | F | 87 | 12 | R | P | 2981 | Stroke | 126 | 97.1 | 88 | 93 |
| DC_392 | M | 56 | 10 | R | PT | 39,068 | Stroke | 108 | 97.6 | 98 | 95 |
| DX_444 | F | 80 | 12 | R | PT | 41,172 | Stroke | 106 | 95.5 | 94 | 93 |
| TS_474 | F | 51 | 11 | R | P | 22,208 | Stroke | 100 | 95.1 | 98 | 95 |
| NS_569 | F | 72 | 18 | R | FT BG | 37,366 | Stroke | 77 | 100 | 100 | 99 |
| DG_592 | F | 45 | 12 | R | PT | 130,552 | Stroke | 127 | 97.8 | 98 | 98 |
| KG_593 | F | 49 | 12 | R | FTP BG | 170,128 | Stroke | 58 | 100 | 90 | 95 |
| KS_605 | M | 63 | 18 | R | C | 23,217 | Stroke | 76 | – | – | – |
| ND_640 | F | 70 | 18 | R | PT | 64,603 | Stroke | 54 | 96.8 | 100 | 100 |
| CS_657 | M | 75 | 18 | R | PO | 33,568 | Stroke | 43 | 99.2 | 98 | 100 |
| KN_675 | M | 64 | 18 | R | FT | 23,779 | Stroke | 32 | – | – | – |
| MN_738 | F | 62 | 16 | R | C | 32,154 | Stroke | 25 | 98.4 | 100 | 100 |

*Key*: F, frontal; T, temporal; P, parietal; O, occipital; BG, basal ganglia; C, cerebellum; I, insula; Pe, peri-Sylvian; PA: pericallosal artery; ACA, anterior cerebral artery; MCA, middle cerebral artery; AVM, arteriovenous malformations. WAB-AQ indicates a composite language score with a maximum possible score of 100. OANB (action) and OANB (object) demonstrate knowledge of verbs and nouns with a maximum possible score of 100.

Macbook Air computer using Matlab 2007 Psychtoolbox. Pictures below an average of 3.5 familiarity rating and below 97% naming agreement were eliminated.

In *the dynamic spatial relations task*, 28 short movie clips depicting five different spatial relations (*put in, put on, move over, move under, move across*) between two objects were used. In each clip, one object was always stationary on a table, and the other object was moved in relation to the stationary object. A male hand illustrated the spatial relation in each movie clip. The clips were filmed with a Sony digital camera in front of a white background on a table (see Fig. 2B for a still picture from a movie clip). Final movie clips were edited using iMovie. Each movie lasted for 3 s. The same volunteers from the previous task rated the familiarity of the objects in the

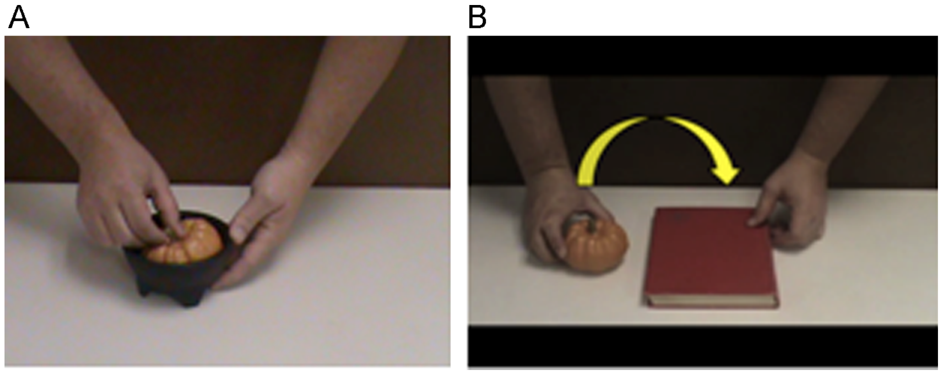


**Fig. 2.** Sample stimuli from the static spatial relations task (A) and the dynamic spatial relations task (B). The target preposition for picture on the left (A) was *in* (i.e., the pumpkin is *in* the bowl). The still frame on the right (B) represents the *put onto* spatial relation. The arrow indicates the direction of the moving object (i.e., the pumpkin was *put onto* the book).

movie clips on a 5-point scale (1 = not familiar at all, 5 = very familiar) and then named the relation between two objects by describing what the moving object did. A total of 54 movie clips were shown to the volunteers. For example, when the participants saw the movie clip of an orange being put in a bowl, they first rated the familiarity of two objects by hitting 1–5 on the keyboard. Then, they described the relation between two objects by saying "the orange was put in a bowl." Two practice trials were presented before the start of the task. Stimuli were presented on a Macbook Air computer using Matlab 2007 Psychtoolbox. The final set of 28 movie clips was selected based on the agreement among the participants. Movie clips below an average of 3.5 familiarity rating and below 97% naming agreement were eliminated.

### 2.3. Procedure

Participants were tested individually in the laboratory or in their homes. In each session, the static spatial relations task was presented before the dynamic spatial relations task. In *the static spatial relations task*, after two practice trials, each participant received 24 test trials in a random order. When a picture was shown on the screen, the experimenter asked the participants to describe the relation between two objects. As in the norming phase, the experimenter started the sentences and the participants completed them. In *the dynamic spatial relations task*, two practice trials were followed by 28 test trials in a random order. After watching the short movie clip on the screen, the experimenter asked the participants to describe what the moving object did in relation to the stationary object. The experimenter presented the pictures and the movie clips on a Macbook Air computer using Matlab 2007 and advanced the trials when the participant was ready. The session was videotaped for further transcriptions of speech and gesture. The experimenter did not mention gestures to the participants or influence their gesturing during the tasks. The neuropsychological tasks were administered on a different testing session either before or after the experimental tasks.

### 2.4. Coding

#### 2.4.1. Speech

Native English speakers transcribed all speech verbatim for participants' responses to each trial. In both tasks, speech for each trial was then coded for the correct preposition.

#### 2.4.2. Gesture

Each participant's spontaneous gestures were transcribed for each trial. A change in the shape of the hand or motion signaled the end of a gesture. For each trial, the coders initially decided whether a gesture was produced. The gestures were classified as (1) static gestures or (2) dynamic gestures. *Static* gestures referred either to objects or to their locative properties. These gestures included pointing at the objects in the pictures and in the movie clips, showing a property of the objects (e.g., making a curved hand shape as the palm faces up to refer to the bowl) or illustrating the static spatial relation between objects (e.g., making a flat hand shape as the palm faces down over the other hand to refer to the preposition 'above'). *Dynamic* gestures involved the movement of the hand in one directional axis (e.g., from left to right or back and forth) or circular movements of the hand. These dynamic gestures mainly represented the dynamic spatial relations between objects such as index finger moving in an arc from left to right to illustrate the preposition 'over'. For the purposes of this study, static and dynamic gestures that referred to spatial relations in a given trial were included for analyses. In particular, these gestures are *iconic* and depict spatial relations between objects statically (e.g., palm faces down put onto the other hand to refer to the preposition 'on') or dynamically (e.g., palm faces down moved from left to right over the other hand to refer to the preposition 'move over').

### 2.5. Reliability

To test the reliability of the coding system, we conducted two types of coding by a second person. First, she randomly chose and coded 20% participants' all responses both for speech and gesture. For the static spatial relations task, agreement between coders was 98.0% ($k$ = 0.897, $n$ = 144 trials) for naming spatial relations, 98.4% ($k$ = 0.872, $n$ = 120 trials) for detecting gestures, and 96.0% for coding gestures that referred to correct spatial relations ($k$ = 0.832, $n$ = 120 trials). For the dynamic spatial relations task, agreement between coders was 98.8% ($k$ = 0.923, $n$ = 168 trials) for naming spatial relations, 99.7% ($k$ = 0.951, $n$ = 168 trials) for detecting gestures, and 96.0% for coding gestures that referred to correct spatial relations ($k$ = 0.836, $n$ = 168 trials).

Second, 20% of each participant's responses both for speech and gesture were randomly chosen and coded. For the static spatial relations task ($n$ = 220), agreement between coders was 97.3% ($k$ = 0.973) for naming spatial relations, 93.4% ($k$ = 0.891) for gesture identification, 96.4% ($k$ = 0.942) for gesture category (static vs. dynamic), and 92.5% for coding gestures that referred to spatial relations ($k$ = 0.912).

For the dynamic spatial relations task ($n$ = 232), agreement between coders was 94.0% ($k$ = 0.940) for naming spatial relations, 97.8% ($k$ = 0.978) for gesture identification, 95.2% ($k$ = 0.931) for gesture category (static vs. dynamic), and 98.7% for coding gestures that referred to spatial relations ($k$ = 0.987).

### 2.6. Analyses

#### 2.6.1. Behavioral analyses

For speech, the dependent variable was the accuracy of naming static spatial relations and dynamic spatial relations in each task. The percentage of correct responses was calculated for each patient. For gesture, two dependent variables were measured: the percentage of trials in which participants produced at least one gesture and the real focus of our study; the percentage of trials in which participants produced spatial iconic gestures.

#### 2.6.2. Neuroanatomical analyses

CT or MRI scans for all patients were rendered to a common anatomical space (Colin27; http://imaging.mrccbu.cam.ac.uk/downloads/Colin). Voxel-based lesion-symptom mapping (VLSM; Bates et al., 2003) analyses were then conducted using Voxbo brain-imaging analysis software developed at the University of Pennsylvania (http://www.voxbo.org). VLSM assessed the relationship between behavioral measures and brain lesions on a voxel by voxel basis. The analyses were restricted to the voxels in which at least two patients had lesions. The analyses resulted in statistical $t$-maps of lesioned brain areas that were significantly related to impaired behavioral performances. We conducted VLSM analyses for speech and gesture dependent variables separately in both tasks. One-tailed $t$-tests for speech and two-tailed $t$-tests for gesture compared behavioral scores between patients with and without lesions at every voxel. The $t$-map for each analysis was thresholded at $q < 0.05$ using the false discovery rate (FDR) to control for multiple comparisons (Benjamini & Hochberg, 1995; Genovese, Lazar, & Nichols, 2002).

## 3. Results

### 3.1. Neuropsychological analyses

Even though most patients were not overtly aphasic, WAB scores were lower for the LHD patients compared to the RHD patients, $F$(1,

23) = 5.75, $p = 0.025$, $\eta^2 = 0.20$ (M = 91.80 and M = 98.13, LHD and RHD, respectively). Both groups did well naming objects and actions and were not significantly different from each other, $ps > 0.05$ (see Table 1). We examined whether action and object naming performances predicted naming spatial relations in our task. Neither the regression model nor the partial correlations were significant, $p > 0.05$.

### 3.2. Speech analyses

One LHD patient created stories with the objects rather than producing prepositions and was excluded from further analyses. A repeated measure ANOVA with the group (LHD, RHD, and HC) as the between-subject variable and the task type (static vs. dynamic) as within-subject variable revealed a main effect of group $F(2, 41) = 7.47$, $p = 0.002$, $\eta^2 = 0.27$. As displayed in Fig. 3, the LHD patients were less accurate than both the RHD patients and HC participants (Scheffé, $ps < 0.05$). No effect of task type or an interaction between group and task type was found. For all participants, the accuracy of both tasks correlated positively, $r = 0.88$, $p < 0.001$. The results of both task types were collapsed in subsequent analyses.

Using VLSM analyses, we found a significant lesion-behavioral relation for producing prepositions. The FDR corrected $t$-statistic threshold with a significance level of $q = 0.05$ was 3.26. As displayed on Fig. 4, lesions to the left posterior middle frontal gyrus, the left inferior frontal gyrus, and the left anterior superior temporal gyrus were associated with impairments in naming spatial relations.

### 3.3. Gesture analyses

Overall, 23 (out of 44) participants produced at least one gesture in the static spatial relations task and 28 participants gestured in the dynamic spatial relations task. To examine the overall use of gestures, we calculated the percentage of trials in which participants used at least one gesture. We then analyzed whether three groups differed in their overall use of gestures in both tasks. A repeated measure ANOVA with the group (LHD, RHD, and HC) as the between-subject variable and the task type (static vs. dynamic) as within-subject variable showed main effects of group and task type, $F(2, 41) = 6.56$, $p = 0.003$, $\eta^2 = 0.24$ and $F(1, 41) = 8.90$ $p = 0.005$, $\eta^2 = 0.18$. No interaction between the group and task type was found. All individuals in each group gestured more frequently in the dynamic task compared to the static task. The LHD patients produced more gestures than the HC group (Scheffé, $p < 0.05$).

Second, we analyzed the use of iconic gestures that referred to the spatial relation (preposition) among three groups. A repeated measure ANOVA with the group (LHD, RHD, and HC) as the between-subject variable and the task type as within-subject variable (static vs. dynamic) showed main effects of group and of task, $F(2,41) = 3.61$, $p = 0.036$, $\eta^2 = 0.15$ and $F(1,41) = 13.44$, $p = 0.001$, $\eta^2 = 0.25$. Again, there were no interactions between group and task. Fig. 5 shows the percentage of trials participants gestured about the locative relationship being depicted. All individuals in each group gestured more frequently in the dynamic task compared to the static task. The LHD patients as a group produced iconic gestures more than the HC participants (Scheffé, $p < 0.05$). VLSM analyses revealed no significant relations between overall gesture use or gestures for spatial relations and lesion site even at a more lenient FDR of 0.10.

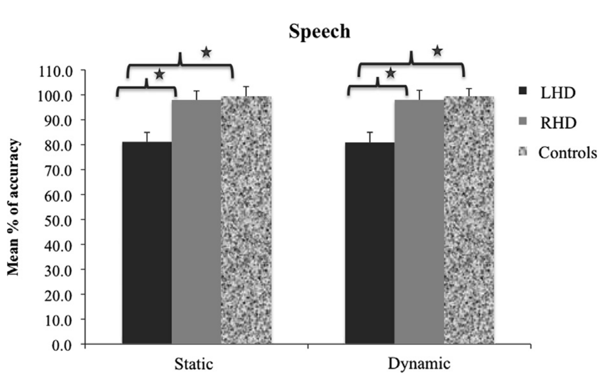


**Fig. 3.** The percentage of trials on which LHD patients, RHD patients, and HC participants correctly produced prepositions in speech in the static and dynamic spatial relations tasks. *$p < 0.05$.

### 3.4. Speech–gesture relations

We initially analyzed whether patients' spatial gestures were produced with speech or whether they produced gestures in isolation. Patients in both groups used gestures with speech more frequently than gestures without speech, $ts > 5.78$, $ps < 0.01$. Nevertheless, LHD patients tended to produce more gestures in isolation (14.8%) than RHD patients (1.2%) in the dynamic task, $F(1, 20) = 3.076$, $p = 0.08$.

We next examined the relation between speech and gesture. For all participants, the use of spatial gestures correlated negatively with the accuracy in naming spatial relations, $r = -0.39$, $p = 0.009$. Subsequent analyses reflect our exploration of the relationship between impaired speech and spatial gesture production.

From the overall pattern of data, an inverse correlation between preposition and gesture production, we infer that spatial iconic gestures are used to help retrieve locative prepositions. However, it remains unclear whether patients with preposition naming deficits were making adequate use of gestures in this manner. For two reasons they might not be doing so. First, a core deficit in representing spatial representations might result in downstream deficits in both lexical and gesture production. Second, the motor circuitry involved in producing spatial iconic gestures might itself be damaged if these circuits lie close to regions involved in producing locative propositions. In either case, participants would not produce as many gestures as predicted by their impairment in producing prepositions. We explore these possibilities in the following manner. First, we identified individual left hemisphere patients with significantly impaired naming performances (Crawford & Garthwaite, 2007). Seven patients were identified as having impaired naming. The LHD patients, without a naming deficit, were combined with the RHD patients and HC participants. From this group of normally performing participants (control participants, the right hemisphere patients, and the unimpaired left hemisphere patients) we used a trendline for the relationship between preposition and gesture production to approximate what would be expected for spontaneous gestures that typically accompany speech. At a first pass, we assume that this relationship is approximately linear. Based on this assumption, we calculated the difference between the actual gesture rate predicted and the gesture rate produced for each participant (i.e., the residual scores). From the unimpaired patients (left and right) and HC participants' residual scores, we computed the standard deviation of the residual scores (SD = 15.71). We then classified the patients from the impaired left hemisphere group ($n = 7$), who were 2 standard deviations above or below the residual distribution of the unimpaired LHD, RHD, and HC participants.

To summarize the logic of this exploratory analysis, we inferred that people normally use gestures to help name spatial relations, which is why there is an inverse correlation between spontaneous gesture and preposition production. At a first approximation, we

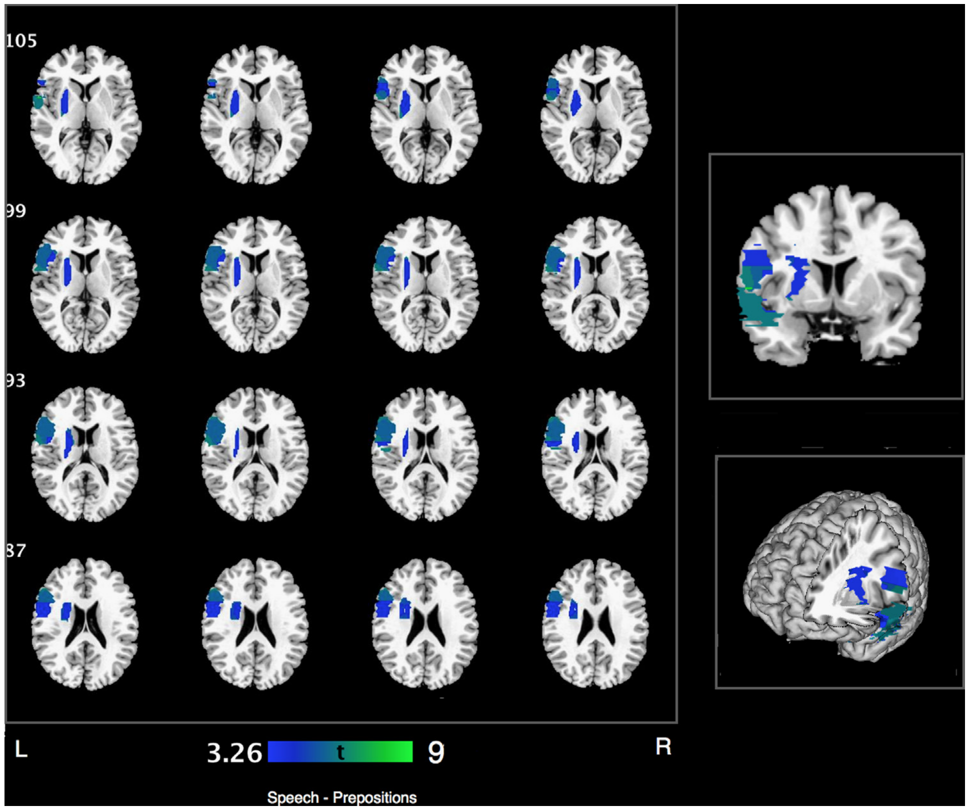


**Fig. 4.** Representative slices from VLSM analyses for the cumulative score of naming spatial relations. The maps show significant $t$-scores with a FDR of $q = 0.05$.

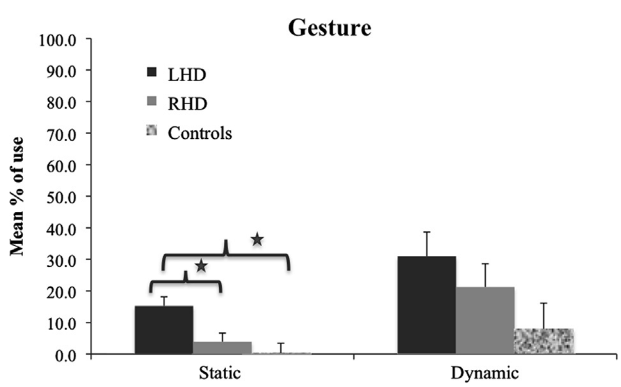


**Fig. 5.** The percentage of trials on which LHD patients, RHD patients, and HC participants correctly produced gestures in the static and dynamic spatial relations tasks. $^{*}p < 0.05$.

assume that this inverse correlation is linear. Based on these inferences and assumptions we found that out of seven patients with preposition naming deficits, two produced the expected use of gestures, and five produced fewer gestures than expected. Finally, we constructed a lesion overlap map for these five patients that produced fewer gestures than expected.

As shown in Fig. 6, the patients that gestured less than expected had lesions that maximally overlapped in the left posterior middle frontal gyrus and the left inferior frontal gyrus.

## 4. Discussion

The purpose of this study was to assess the neural basis of naming spatial relations. To do so, we examined unilateral focal brain-injured patients' performance in producing locative prepositions. The investigation was motivated by the hypothesis that neural structures involved in accessing these prepositions would be aligned with or close to neural structures that are involved in perceiving comparable spatial relations. We also investigated the relationship of patients' impaired of spatial relations and their use of spontaneous co-speech gestures.

As a group, LHD patients performed worse than RHD patients in naming spatial relations between objects. In particular, patients with lesions in the left posterior middle frontal gyrus, the left inferior frontal gyrus, and the left anterior superior temporal gyrus were impaired in producing locative prepositions. The use of spatial gestures negatively correlated with naming accuracy suggesting that gestures generally aid or compensate for difficulty with producing locative prepositions. However, our results also suggest that LHD patients who had damage to the left posterior middle frontal gyrus and the left inferior frontal gyrus might not gesture as much as expected to compensate for their impairments in naming spatial relations.

### 4.1. *The neural basis for naming spatial relations*

We found that lesions to three main areas – the posterior middle frontal gyrus, the inferior frontal gyrus, and the anterior superior temporal gyrus – were linked to poor performance in naming prepositions. Our results are consistent with earlier findings (Amorapanth et al., 2009; Damasio et al., 2001; Kemmerer & Tranel, 2003; Tranel & Kemmerer, 2004; Noordzij et al., 2008). In particular, the relation between frontal regions and processing of spatial relations, either in comprehension or production, was found in these previous studies. This finding also corroborates lesion studies with Broca's aphasics that report impaired processing of locative prepositions (e.g., Friederici, 1981, 1982; Tesak & Hummer, 1994; Kemmerer & Tranel, 2003). One of the prominent neural correlates for locative prepositions is globally found to be

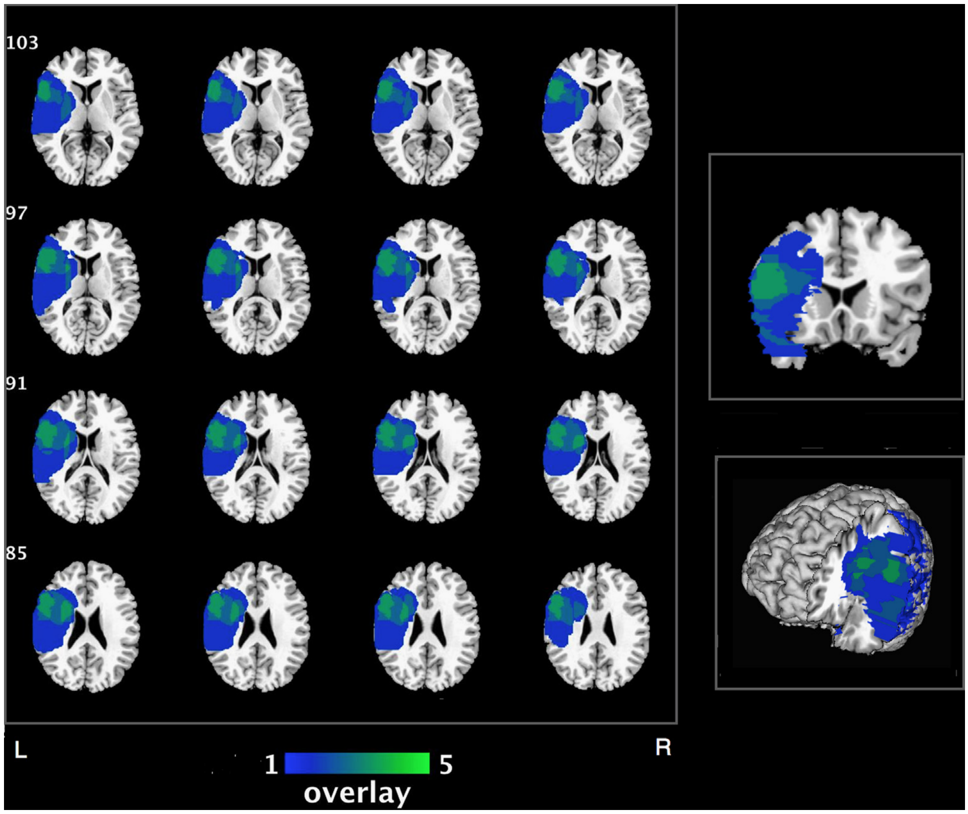


**Fig. 6.** Lesion overlays for the left hemisphere patients who gestured less than the predicted gesture rates based on their impaired speech scores from the trendline from the unimpaired controls and patients.

the inferior fronto-parietal cortices (Amorapanth et al., 2009; Chatterjee, 2008; Damasio et al., 2001; Kemmerer, 2006; Tranel & Kemmerer, 2004; Wu et al., 2007). This area was also activated in an fMRI study that examined the processing of dynamic spatial relations (i.e., the paths of actions) (Wu et al., 2008). These observations are consistent with the hypothesis that the frontal eye fields serve as a sensory-motor point of entry for locative information that is lexicalized within closely aligned neural structures.

We did not find that parts of the left inferior parietal lobule were critical in naming locative prepositions. There are two possibilities for this negative finding. First, this region may be important for verbal matching of locative relations (Amorapanth et al., 2009), but not for the production of prepositions. Second, we may have lacked sufficient power to detect effects of damage to this area. When looking at the three LHD patients with parietal damage, one case (BC_236) who had supramarginal gyrus damage and impaired preposition naming also had lesions to the frontal cortex and the superior temporal gyrus. In contrast, the other two left patients (NS_604 and KM_642) who had lesions in the superior parietal and the parietal–occipital areas, but sparing supramarginal gyrus, did not have impaired preposition naming. Thus, we remain agnostic about the role of the IPL, especially the supramarginal gyrus, in naming locative relations.

With respect to the left temporal cortex, fewer studies reported the specific involvement of this area for processing spatial relations (Amorapanth et al., 2009; Damasio et al., 2001). However, our finding is consistent with the study of Amorapanth et al. (2009), which demonstrated that categorical spatial relation deficits were linked to damage to the white matter undercutting the anterior superior temporal gyrus. Wu et al. (2007) also found that damage to the anterior superior temporal gyrus produced impairments in matching locative sentences, such as "the circle is above the square," to the appropriate pictures. The left anterior superior temporal gyrus is typically considered to be involved with comprehension and production of the semantic aspects of language (e.g., Borovsky, Saygin, Bates, & Dronkers, 2007; Dronkers, Wilkins, Van Valin, Redfern, & Jaeger, 2004). Together with the other findings from our lab (Amorapanth et al., 2009; Wu et al., 2007), we suggest that the left superior temporal gyrus is also involved in naming spatial relations between two objects.

Finally, the left hemisphere patients did not display global impairment in language, since naming objects and actions did not predict accuracy in naming prepositions. This finding supports the results from a pair of case studies by Kemmerer and Tranel (2003) who found that one patient with a lesion to the left inferior and middle premotor/prefrontal region had impairment with the meanings of action verbs. In contrast, another patient who had damage to the left inferior parietal lobe and the left posterior superior temporal region presented difficulty with the meanings of prepositions. Thus, dissociations naming different classes of words occur not only between objects and actions (Caramazza & Hillis, 1991; Vigliocco, Vinson, Druks, Barber, & Cappa, 2011), but also among objects, actions, and prepositions.

### 4.2. The (dis)associations between speech and gesture

This is one of the first studies to probe the relationship between locative preposition and spontaneous gesture production. Our findings potentially reconcile what seems like contradictory claims in the literature: that aphasic patients gesture more frequently than non-aphasic patients, and that they gesture less frequently than expected. First, both patient groups produced more gestures that referred to objects and spatial prepositions than the control participants. Second, all groups used gestures more frequently in the dynamic context. Third, the use of spatial gestures negatively correlated with naming accuracy. Although we did not find specific lesions related to spontaneous gesture use, our exploratory results from patient lesion overlap suggested that lesions to the dorsolateral prefrontal cortex might influence compensatory gestures for impaired speech.

Our results provide support both for the complementary and compensatory roles of gestures to speech. Individuals with intact speech produced gestures together with the verbal information. People reinforced their speech with gesture and they represented similar information in both modalities. For example, when saying "moving over," a participant made an arc gesture from left to right. In these instances, speech and gesture are coupled and convey related meanings (McNeill, 1992). Patients, who have brain injury, particularly in the left hemisphere, might still depend on gestures to organize their thoughts for spatial information (Alibali et al., 2000).

Although participants conveyed the same spatial information in speech and gesture on most trials, in 15% of the trials for the dynamic task, the LHD patients only conveyed the correct spatial information with gestures. Further accuracy in naming locative prepositions was negatively correlated with the rate of spatial gesture production. These data suggest that impaired speech from left hemisphere injury does not necessarily lead to impairment in gestures, corroborating prior findings with Broca's aphasics (Feyereisen, 1983; Hadar et al., 1998; Kemmerer et al., 2007; Lanyon & Rose, 2009; Le May et al., 1988). Our interpretation of the data presented here supports both dissociations and associations between gesture and speech in the context of producing spatial prepositions.

Tentatively, we suggest that the normal tendency to use gestures to compensate for speech impairment is also affected by damage to the left posterior middle frontal gyrus and the left inferior frontal gyrus. Even though LHD patients as a group gestured more frequently than the RHD patients, some of them gestured less than expected. These patients might not only have problems with lexical retrieval, but also with accessing spatial concepts. Alternatively, the motor programs for gesture output might have also been disrupted. Our finding of an impairment in producing prepositions and spatial gestures with lesions to left inferior frontal cortex corroborates previous research that suggested a role for this area in both language processing and co-speech gestures (Willems et al., 2007). Future research is necessary to specifically test this hypothesis.

We did not assess our subjects for praxis. Some of these patients may have had common motor programming deficits that could result in downstream spontaneous gestures and praxis impairments. Since apraxia itself can occur at multiple levels, and spontaneous gestures vary from praxis in their explicitness, complexity, and representational underpinnings (drawing on spatial relations here vs. tool knowledge/skilled movements) we would need carefully designed future studies to dissect the relationship between spontaneous spatial gestures and praxis systems.

In sum, we propose that focal brain injured patients use gestures both to complement intact speech and to compensate for impaired speech. Yet, damage to the specific parts of dorsolateral prefrontal cortex may impair the production of spontaneous gestures that normally compensate for these naming difficulties.

## 5. Conclusions

In this study, we investigated the neural correlates of the naming locative prepositions in patients with unilateral brain injury and the extent to which impairments in naming prepositions would lead to gesture production. Our results show that damage to the left posterior middle frontal gyrus, the left inferior frontal gyrus, and the left anterior superior temporal gyrus produced deficits in naming spatial relations. The ability to compensate for speech with gesture might also be impaired particularly when patients have lesions in the left posterior middle frontal gyrus and the left inferior frontal gyrus. This suggests that gestures might not entirely help replacing problems about naming spatial relations.

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