

Language, perception, and the schematic representation of spatial relations

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ABSTRACT

Schemas are abstract nonverbal representations that parsimoniously depict spatial relations. Despite their ubiquitous use in maps and diagrams, little is known about their neural instantiation. We sought to determine the extent to which schematic representations are neurally distinguished from language on the one hand, and from rich perceptual representations on the other. In patients with either left hemisphere damage or right hemisphere damage, a battery of matching tasks depicting categorical spatial relations was used to probe for the comprehension of basic spatial concepts across distinct representational formats (words, pictures, and schemas). Left hemisphere patients underperformed right hemisphere patients across all tasks. However, focused residual analyses using voxel-based lesion-symptom mapping (VLSM) suggest that (1) left hemisphere deficits in the representation of categorical spatial relations are difficult to distinguish from deficits in naming these relations and (2) the right hemisphere plays a special role in extracting schematic representations from richly textured pictures.

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1. Introduction

Can abstract meaning be represented without language? Although it is clear that we can think about concrete concepts without language, it is difficult to know how to best characterize mental representations of abstract concepts that are both meaningful and non-linguistic (Mandler, 2000). A place to start could involve observing how abstract semantic information is intentionally transmitted without either the aid of words or concrete imagery. Abstract graphics have been used to convey such meanings long before humans kept formal history. Map-like cave drawings rendered over 6000 years ago appear to make use of simplified visual elements like dots, lines, and rectangles to represent the abstract spatial topologies and arrangements of dwellings, paths, or crops (Chippindale & Nash, 2004; Smith, 1982). Pictograms and calendars were used for communicating important, highly abstract forms of cultural information—about commercial transactions or seasonal events, for example—before the advent of full-blown symbolic writing systems (Garrod, Fay, Lee, Oberlander, & MacLeod, 2007; Tversky, 2001). What maps, pictograms, and calendars have in common is that each compacts a more complex reality into a simplified, or “boiled down” representation that preserves

something about the meaning of the thing it represents. Most generally, the term **schema** is used in this paper as any kind of representation (external or cognitive) where perceptual detail has been abstracted away from a complex scene or event while preserving critical aspects of its analog qualities. Schemas, as such, occupy a representational middle-ground: more abstract than very concrete representations of objects, but unlike truly symbolic representations (e.g., words) a schema preserves some of the spatial-relational aspects of the thing it stands in for. The most critical aspect of schemas, as the term will be employed in the present paper, is that they occupy an intermediate position between abstract words and concrete percepts in a graded model of representation (Chatterjee, 2001). Although dissociations on concrete word and picture comprehension tasks have been reported (Saffran, Coslett, Martin, & Boronat, 2003), intermediate formats like schemas have not been thoroughly investigated.

In the history of ideas, the term *schema* has made several appearances in philosophy (Kant, 1781/1998), neurology (Head & Holmes, 1911), and psychology (Bartlett, 1932; Piaget, 1952; Schank & Abelson, 1977). The term has resurfaced in the relatively nascent field of cognitive linguistics (Johnson, 1987; Lakoff & Johnson, 1999; Mandler, 1992; Talmy, 2000) to describe the mental representations that code for the kinds of abstract spatiotemporal relations among objects—like paths, containment, contact, and support relations—theorized to provide a conceptual base onto which language can be mapped, and it is in this context that we employ the term. Although schemas are often depicted externally as static icons or diagrams (Peirce, 1955), internal schematic mental representations

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are better understood as multimodal abstractions of frequently occurring patterns of movement, spatial relations, and force dynamics. While a good deal about spatial schemas has been written within cognitive linguistics, virtually nothing about their neural organization is known. In cognitive neuroscience, research in this general area has focused on the representation of prepositions. Work by Frederici (1981) demonstrated that Wernicke aphasics have impairments in processing locative prepositions. Landau and Jackendoff (1993) subsequently proposed that the parietal cortex, by virtue of being the terminus of the dorsal “where” pathway, might process prepositions. This hypothesis was corroborated by work from Damasio and colleagues demonstrating a role for left supramarginal gyrus and inferior frontal gyrus in the comprehension of locative prepositions (Damasio et al., 2001; Emmorey et al., 2002). Noordzij, Neggers, Ramsey, and Postma (2008) also found that understanding the kind of categorical spatial relations expressed by locative prepositions was associated with activation in the left supramarginal gyrus. And Wu, Waller, and Chatterjee (2007) found locative relations to be mediated by left inferior frontal–parietal cortices. The overall picture that emerges from both the literature on prepositions and that on categorical spatial relations is one that strongly implicates the left hemisphere over and above the right.

We are interested in how spatial meanings are accessed—like when we use simple verbal labels to describe the spatial relations of objects arrayed in perceptually rich scenes, but also when we make use of simplified schemas. Also, we wish to better understand whether the brain distinguishes between paired-down, externalized depictions of spatial schemas and other information formats like words and pictures. Although our design represents a necessary first step in probing for neural evidence of mental schemas, it should be noted that the “schemas” we later introduce as stimuli represent mental schemas as much as “words” and “pictures” represent language and object perception in the brain. The present set of schematic stimuli was designed to highlight any unique processes associated with their mental representation over and above other representational formats.

The current study attempts to distinguish between those brain areas responsible for representing spatial relations (1) in rich perceptual detail, (2) at an intermediate level of schematic abstraction as described above and, (3) with language. Schemas are more concrete compared to the arbitrary letters and sounds that represent a word like “IN” and more abstract than photographs or drawings depicting real world scenes in space.

Despite cognitive neuroscience’s growing interest in exploring relations between space and language, very little is known about the neural organization of schematic representations. Up to this point, spatial schemas have largely been a theoretical construct. Our aim was to take an empirical approach. Work from our lab, as well as others’, implicates areas within the left hemisphere, specifically inferior parietal lobe and frontal operculum, as being involved in the representation of categorical spatial relations of the type that are encoded by locative prepositions (Amorapanth, Widick, & Chatterjee, 2010; Damasio et al., 2001; Noordzij et al., 2008; Tranel & Kemmerer, 2004; Wu et al., 2007). The main hypotheses being tested in the current study concern the extent to which the left or right hemisphere shows a preference for schematic representation and the extent to which schematic representations are distinguished from language on the one hand, and from rich perceptual representations on the other. As suggested by previous research, damage to the left hemisphere in areas postulated to be critical for the representation of lexicalized categorical spatial relations might, in parallel, compromise their schematic representation. Alternatively, right hemisphere areas critical for the representation of nonverbal spatial information may be implicated in representing such abstract *meaning without language*. The mediating role that schemas are hypothesized to play between language

and perception in representing the meaning of categorical spatial relations suggests that either of the above principles of neural organization could be the case. We sought to test the validity of these two alternative hypotheses.

2. Methods

2.1. Stimuli

The behavioral data we discuss below was collected as part of a larger assessment using portions of a spatial battery currently under development at the University of Pennsylvania. The spatial battery contains several separate sections with stimuli designed to probe distinct forms of spatial information processing (e.g., categorical vs. coordinate, or static vs. dynamic spatial information) using several spatial cognition tasks (e.g., matching or memory tasks). The present study investigated the neural basis of spatial information using matching tasks depicting static categorical relations across different representational formats (i.e., verbal, perceptual and schematic).

2.1.1. Word and picture selection

To administer a balanced and controlled set of stimuli, we selected prepositions to serve as the **words** in our matching tasks according to two main preposition classes described in the literature (Talmy, 1996, 2000). Most simply: *topologic* prepositions describe figure-ground relations that vary along the dimensions of contact and degree of enclosure (e.g., IN and ON), and *projective* prepositions describe figure-ground relations that vary along the dimensions of vertical or horizontal displacement (e.g., ABOVE and BELOW). Each matching task used 4 unique spatial concepts: two topological and two projective. These prepositional classes were selected because they describe static spatial relations.

For the **pictures** in our matching tasks, we used realistic color image stimuli from the spatial battery. The selected pictures were designed to unambiguously depict the same spatial relations denoted by the prepositions. Real objects were photographed and the resulting digital images were processed in Photoshop for optimal clarity. The objects in these pictures consisted of a small set of relatively common household or office items that could function as the figure or ground object for the locative relations being tested (e.g., a pair of scissors, a mug, a fork, a cutting board). As much as possible, we used the same objects, arranged in different ways, to depict distinct lexicalized spatial relations. Twelve unique photographs were available for each of the four spatial relations used in the matching tasks.

2.1.2. Schema construction

We constructed **schemas** consisting of simple lines and geometric forms using graphic-making tools in Photoshop. This set of schemas varied along parameters proposed by Talmy (1996), such as containment, support, and degree of separation. These images, consisting of simple lines and geometric forms depicting clear figure-ground relations, were paired with locative prepositions in a forced-choice task. Across all schemas, the *figure* object was colored red and the *ground* object was colored black. Six normal participants rated an initial set of schemas (20–24 per preposition) with respect to how well each represented an exemplar for a particular preposition. The ten most highly rated schemas for each preposition were used for the experimental matching tasks (see examples in Fig. 1).

2.2. Participants

Written informed consent in accordance with the procedures of the Institutional Review Board of the University of Pennsylvania was obtained for all participants in this study.

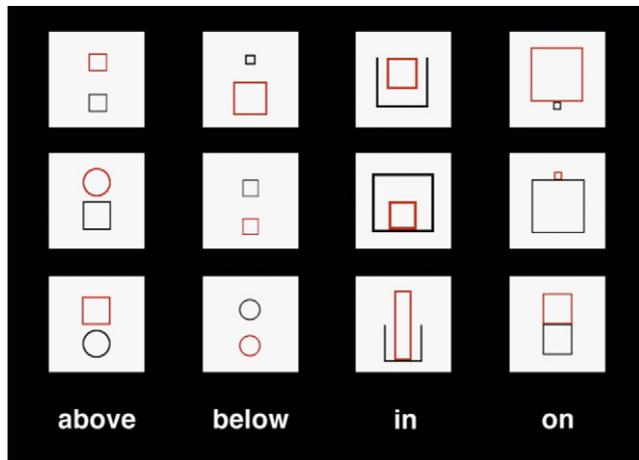


Fig. 1. Representative schematic images used in the schema matching tasks. Figure objects were denoted in red, ground objects in black.

2.2.1. Patient groups

(See Table 1 and Fig. 2.) 17 right hemisphere damaged (RHD) and 17 left hemisphere damaged (LHD) patients ranging from 48 to 85 years of age (RHD: mean = 60.4; LHD: mean = 60.9) with chronic lesions of at least 6 months duration (RHD: mean = 92.8; LHD: mean = 89.4) were recruited from the Focal Lesion Patient Database (Center for Cognitive Neuroscience, University of Pennsylvania). Post hoc analyses indicated that, as compared to the RHD group, the LHD participants had significantly more lesioned voxels [RHD: mean = 34076.8; LHD: mean = 77799.5; $t(32) = 2.38$, $p < .05$]. The subjects were not selected on the basis of specific behavioral criteria, except that patients with a history of other neurological disorders affecting the central nervous system or psychiatric disorders are excluded from the patient database. All subjects were native English speakers and right handed. Each participant was tested individually. All spoken materials were delivered by a native English speaker. In the event that the subject was unable to complete testing in one session, additional sessions were scheduled at least one week later.

2.2.2. Screening tasks

AMNART: The American National Adult Reading Test (Grober & Sliwinski, 1991) was administered in the course of neuropsychological screening and a score was computed for each patient. This task provided an assessment of patients' verbal ability. Greyscales Test for Neglect: The Greyscales task (Mattingley et al., 2004) was administered and a score was computed for each patient. This task was conducted to obtain an assessment of patients' abilities to allocate attention.

Object Matching Task: See Fig. 3. This task was specifically designed for the present study to assess patients' general ability to perform a matching task (with words and pictures) but in the absence of the particular spatial-relational demands of interest. This control task was presented using the same stimulus design used in the four spatial-relational matching tasks (below). Specifically, it was intended to ensure that participants (1) understood the general matching-task instructions across the study, could (2) process single words in the context of a matching task, and (3) find the items for selection in the matching task arrays. Subjects were presented with 32 trials in which a probe consisting of an object name was to be matched with a picture of that object from a field of four choices. Subjects indicated which one of four pictures depicted the correct answer either by pointing or by reading the letter underneath a particular image. These were

the same objects used in pictures depicting spatial relationships in the experimental tasks.

2.2.3. Age-matched controls

Six neurologically healthy participants ranging from 48 to 73 years of age were tested on tasks identical to those completed by the patient groups. All control participants were native English speakers and right handed. Each was tested individually. All spoken materials were delivered by a native English speaker.

2.3. Procedure

2.3.1. Spatial matching tasks

Incorporating the three basic types of stimuli described above (words, pictures, and schemas) we used four matching tasks to investigate cognitive processing across representational formats. All tasks required participants to match a relation depicted in a probe item to one of four target items: either matching pictorial or verbal spatial relations to an explicit schema (tasks 1 and 2) or matching them to a picture (tasks 3 and 4). See Figs. 4–7. Each of the four tasks consisted of 22 trials. Individual probe items depicted one of four discrete spatial relations used in each task. All tasks in the present study used two unique spatial probes representing topological relations (e.g., IN or ON) and two representing projective relations (e.g., ABOVE or BELOW).

2.3.1.1. Picture–schema matching. This task was designed to assess patients' abilities to abstract spatial concepts from different photographic representations and match them to simplified representations consisting of lines and geometric figures. Patients were presented with a probe photographic image situated adjacent to four schematic target images.

Among the four targets to choose from, one correctly depicted the spatial relationship in the probe image, one depicted a within-class relation, and two depicted across-class relations (Fig. 4). Foils were distributed as such in all four tasks. For each task, subjects indicated which one of four pictures or schemas depicted the correct answer either by pointing or by reading the letter underneath a particular image. Note: because the trials reported here were part of a larger battery of spatial tasks, foil types sometimes reflected categories of spatial relations (e.g., dynamic path relations) or particular items (e.g., “left of”) that were not included in the present analysis.

2.3.1.2. Word–schema matching. This task was designed to test patients' abilities to extract the appropriate spatial meaning from locative prepositions and match them to simplified schematic representations. Word probes were presented adjacent to four target schemas as in the picture–schema matching task (Fig. 5).

2.3.1.3. Word–picture matching. This task was designed to test patients' abilities to extract the appropriate spatial meaning from locative prepositions and match them to one of four photographic representations. Patients matched a probe word to one of four target images containing different pairs of objects (Fig. 6).

2.3.1.4. Picture–picture matching. This task was designed to assess patients' ability to generalize categorical spatial concepts across different photographic representations. Patients matched a probe photograph containing one pair of objects in a particular spatial relationship to one of four target images containing different pairs of objects (Fig. 7).

Table 1

Patient information. Overall accuracy refers to the average percent correct across the four spatial-matching tasks. TPO stands for *Time Post Onset* or months since stroke at time of testing.

Lesioned hemisphere	Overall accuracy (%)	General deficit? (>3SD)	Age	Gender	Education (years)	TPO (months)	Lesion site	Lesion volume (voxels)	Reason for damage
LEFT	80.68	YES	44	M	12	93.7	Frontal–temporal	163,270	Stroke/Infarct
LEFT	25.00	YES	64	M	12	87.0	MCA	202,172	Stroke/Infarct
LEFT	92.05	NO	58	F	15	115.4	Insula	6052	Stroke/Infarct
LEFT	84.09	NO	76	M	23	143.7	Parietal–temporal	128,330	Stroke/Infarct
LEFT	37.50	YES	50	M	12	84.8	MCA	133,464	Stroke/Infarct
LEFT	87.50	NO	60	M	18	149.3	Frontal–parietal	139,559	Stroke/Infarct
LEFT	89.77	NO	70	M	12	98.7	Parietal	29,172	Stroke/Infarct
LEFT	56.82	YES	81	M	11	62.1	Parietal	44,552	Stroke/Infarct
LEFT	65.91	YES	53	F	12	65.3	Occipital–temporal, centrum semiovale	34,481	Stroke/Infarct
LEFT	69.32	YES	53	M	12	55.6	Temporal, basal ganglia	27,587	Stroke/Infarct
LEFT	79.55	YES	67	M	12	61.9	Frontal	24,326	Hemorrhage
LEFT	90.91	NO	43	F	13	53.0	Frontal, insular cortex	36,259	Stroke/Infarct
LEFT	83.33	YES	80	F	16	232.9	Temporal–parietal–occipital	139,533	Stroke/Infarct
LEFT	52.27	YES	71	M	12	42.5	Parietal–temporal, ACA/MCA watershed	136031	Stroke/Infarct
LEFT	86.36	NO	40	F	18	129.4	Frontal	61,659	Stroke/Infarct
LEFT	51.14	YES	44	F	12	27.5	Frontal, parietal	10,956	Stroke/Infarct
LEFT	81.82	YES	76	M	21	16.4	Parietal	5188	Stroke/Infarct
RIGHT	86.36	NO	65	M	12	109.8	Frontal–temporal–parietal	7549	Stroke/Infarct
RIGHT	94.32	NO	66	F	16	110.9	Frontal	10,293	Stroke/Infarct
RIGHT	92.05	NO	53	F	18	368.0	Temporal, Basal ganglia	51,084	Stroke/Infarct
RIGHT	90.91	NO	79	F	18	99.2	Frontal	27,912	Stroke/Infarct
RIGHT	85.23	NO	57	F	16	330.3	Parietal	28,333	AVM
RIGHT	76.14	YES	82	F	12	66.5	Parietal	37,607	Stroke/Infarct
RIGHT	87.50	NO	51	M	10	56.8	Parietal–temporal	39,203	Stroke/Infarct
RIGHT	82.95	YES	75	F	12	46.7	Parietal–temporal	13,442	Stroke/Infarct
RIGHT	80.68	YES	46	F	11	44.7	Parietal	21,612	Stroke/Infarct
RIGHT	89.77	NO	65	F	12	51.6	Frontal–temporal	37,072	Stroke/Infarct
RIGHT	92.05	NO	55	F	12	65.4	Temporal–parietal, basal ganglia,	18,097	Stroke/Infarct
RIGHT	82.95	YES	59	M	12	34.6	Parietal, frontal	2494	Stroke/Infarct
RIGHT	85.23	NO	73	F	10	56.1	Frontal, parietal	1826	Stroke/Infarct
RIGHT	95.45	NO	68	F	18	16.0	Frontal–temporal, basal ganglia	33,260	Stroke/Infarct
RIGHT	87.50	NO	54	F	16	51.2	Parietal	6812	AVM
RIGHT	85.23	NO	39	F	12	61.8	Frontal–parietal	93,662	Stroke/Infarct
RIGHT	73.86	YES	45	F	12	7.7	Frontal–temporal–parietal, basal ganglia, caudate	14,9030	Stroke/Infarct

2.4. Analyses

2.4.1. Neuroanatomical analyses

Lesions were segmented and co-registered using a manual procedure with MRICro (Rorden & Brett, 2000). A T1-weighted MNI template image was first rotated pitchwise into correspondence with the patients' scans. An experienced neurologist outlined the lesions on the template, resulting in a map in which each voxel was labeled either 0 (intact) or 1 (lesioned). Finally, the lesion maps were rotated back into a canonical MNI orientation, using nearest-neighbor interpolation to restrict the map values to 0 and 1 using an automated feature of MRICro. For most of the subjects, lesions were drawn on a $2 \times 2 \times 2$ mm template. For those originally drawn at higher resolution, we first resampled the lesions to $2 \times 2 \times 2$ mm for the purposes of performing the interpolation.

2.4.2. Voxel-based lesion-symptom mapping (VLSM) analyses

Using brain-imaging software developed at the University of Pennsylvania (www.voxbo.org), *t*-tests compared behavioral scores between patients with and without lesions at every voxel for each lesion map (RH and LH maps were analyzed separately). We restricted our analyses to voxels in which at least 2 patients had lesions. Fig. 9a and b illustrates voxels in RHD and LHD participants where at least 2 patients' lesions overlapped. The *t*-map for each analysis was thresholded to control the False Discovery Rate (FDR) at $q = 0.05$. FDR control was achieved with a procedure first described by Benjamini and Hochberg (1995) and

adapted for brain image analysis by Genovese, Lazar, & Nichols (2002). The procedure identifies a threshold that controls the expected proportion of false positives. In our dataset, selecting a false discovery rate (*q* value) of 0.05 yields a *t* threshold. This means that of the total number of voxels in an analysis with *t* values exceeding this threshold, the expected proportion of false positives is 0.05.

In order to contrast the neural bases for particular representational formats (words, schemas, and pictures), we use VLSM analyses of residual scores (Amorapanth et al., 2010). The matching tasks in the present study, despite moving between distinct representational formats, were similar enough that performance on each was expected to be significantly correlated. All tasks tested participants' fluency with categorical spatial relations. When behavioral performance across two tasks are correlated, residual scores based on regression analyses can be used to probe for task-specific sources of variance using VLSM. This is achieved by calculating the residual scores of one task regressed onto another and pairing these scores with lesion data in VLSM analyses. The method segregates regions of vulnerability for a particular task that cannot be accounted for by vulnerability for another correlated task (and *vice versa*). Furthermore, in the present study, when two residualized matching-tasks share a common representational format between them (e.g., word–**schema** and picture–**schema** tasks have schemas in common), differences in residual VLSM analyses is best explained by what differs (words and pictures). For the above example, this results in a more targeted contrast between word and picture formats while

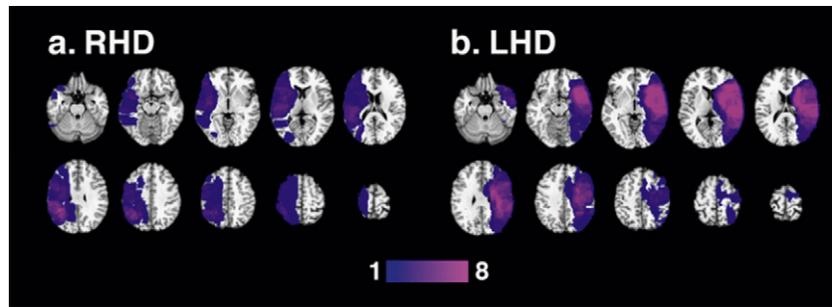


Fig. 2. Coverage map illustrating lesion sites for all participants.

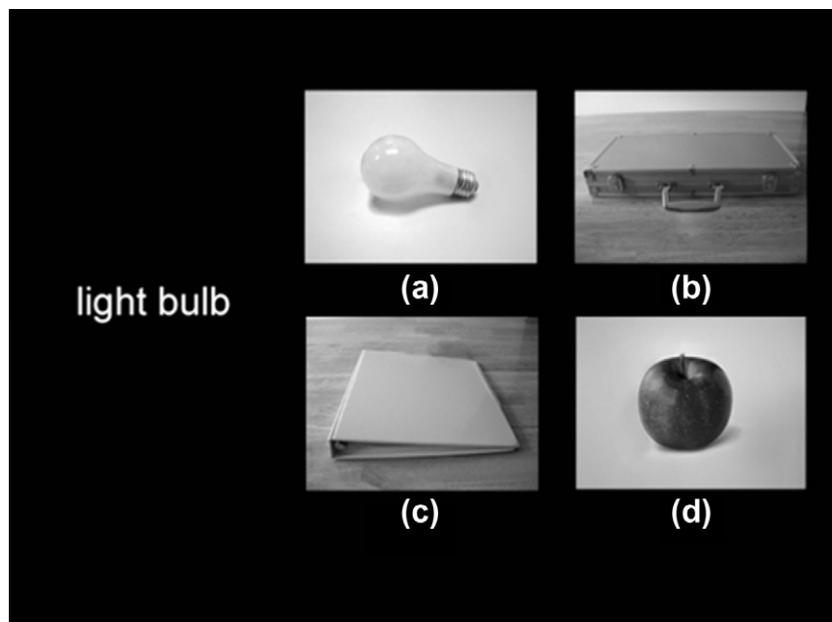


Fig. 3. Sample object matching trial. Original in color.

schema processing is held constant. Analogous with more common fMRI methods, VLSM residual analyses are designed to isolate discrete sources of variance using condition-relative, or “contrast-like” measures, while treating shared features between tasks as “nuisance” covariates.

3. Results and discussion

3.1. Screening tasks

American National Reading Test (AMNART): As expected, LHD participants displayed worse performance on this measure than RHD participants. (Average scores for LHD and RHD groups were 56.5 and 116.9, respectively.)

Greyscales: LHD participants did not significantly display more evidence of neglect of contralateral visual space than participants in the RHD group (average scores were -0.11 . vs. 0.10 , respectively). Possible scores could vary between -1.0 and $+1.0$, with negative scores indicating a leftward bias and positive scores indicating a rightward bias.

Object Matching Task: All testing groups performed above 95% for this task (LHD group: $M = 96.6\%$; $SD = 4.88$; RHD group: $M = 98.7\%$; $SD = 1.81$; Controls: $M = 100\%$; $SD = 0.00$), with no significant differences across groups. This suggests that all participants understood the general matching-task instructions and could find the items for selection. Furthermore, it suggests that

no individual participants had reading deficits so severe that they could not process single words as such in the specific context of the present matching task (despite predictable group differences between LHD and RHD participants' AMNART scores).

3.2. Behavioral results

Behavioral performances for all groups on all matching tasks are shown in Fig. 8. An analysis of errors by type (incorrect choices could be either [1] within or [2] between preposition class) indicated no differences for any of the participant groups or tasks.

Table 1 reports individual participants' average accuracy scores across all four tasks. Patients whose average score was 3SD lower than that for the control group ($M = 91.10\%$; $SD = 2.43$) were categorized as having a general task deficit. In total, 11 LHD and 5 RHD participants had general task deficits. A main benefit of VLSM techniques using residual scores is that these participants can be included in the final analyses.

3.2.1. Picture–schema task

The LHD group was the most impaired on this task (average accuracy = 62.30% , range = 18.18 – 90.91% ; $S_E = 5.98$). They scored significantly lower than the RHD group [average accuracy = 82.09% , range = 54.55 – 95.46% ; $S_E = 2.60$; $t(32) = 2.93$, $p < .01$] and the control group [average accuracy = 84.85% , range = 78.1 – 90.9% ; $S_E = 2.80$; $t(21) = 3.41$, $p < .01$]. The difference between the RHD group and the control group was not significant.

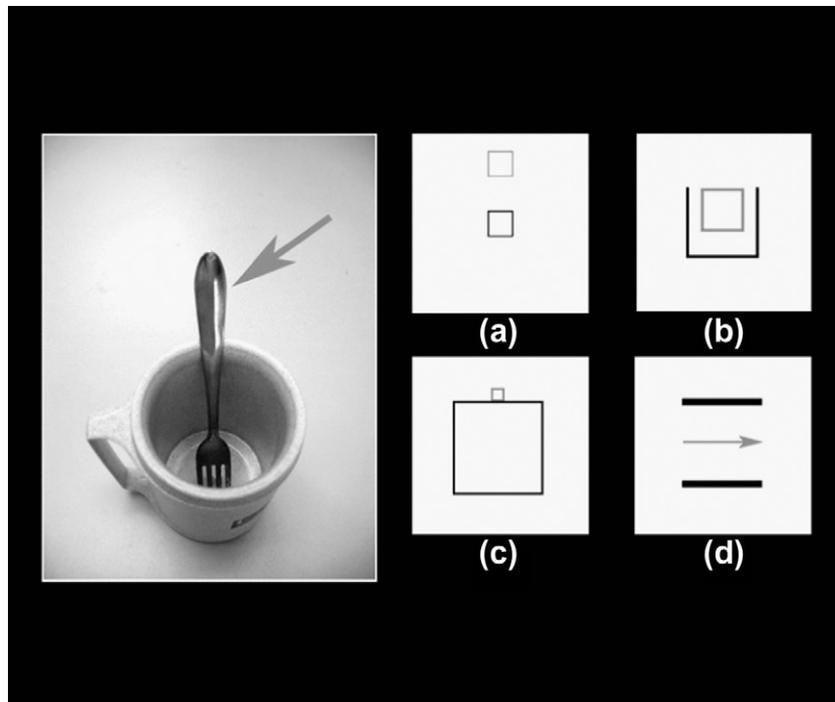


Fig. 4. Sample picture–schema stimulus for *in*. Foils A and D are across class foils, belonging to projective (*above*) and path (*through*) classes, respectively. Foil C is the within class foil (*on*) and B is the correct answer. Original in color.

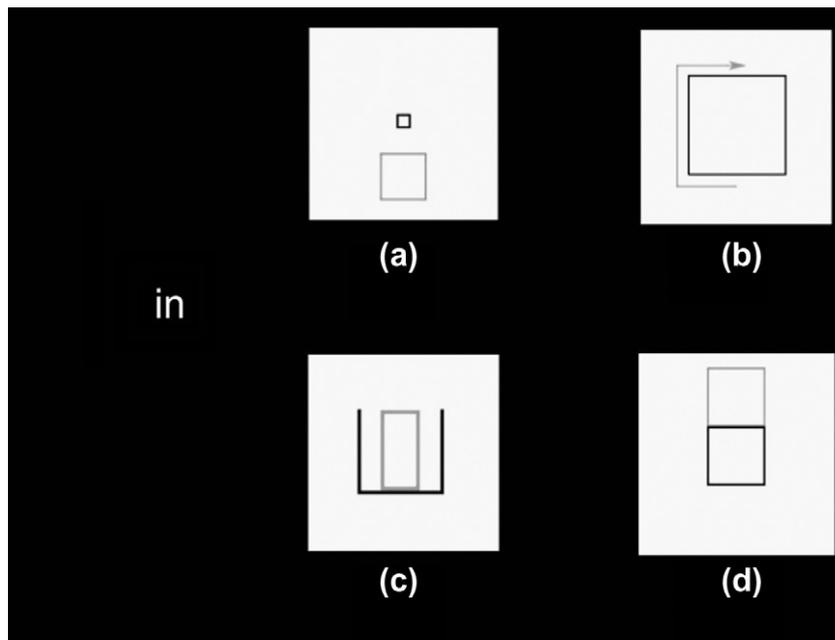


Fig. 5. Sample word–schema stimulus for *in*. Foils A and B are across class foils, belonging to projective (*below*) and path (*along*) classes, respectively. Foil D is the within class foil (*on*) and C is the correct answer. Original in color.

3.2.2. Word–schema task

The LHD group was the most impaired on this task (average accuracy = 66.48%, range = 27.27–95.45%; $S_E = 5.39$). They scored significantly lower than the RHD group [average accuracy = 88.24%, range = 63.64–100%; $S_E = 2.65$; $t(32) = 3.47, p < .01$] and the control group [average accuracy = 93.93%, range = 90.9–100%; $S_E = 1.92$; $t(21) = 4.64, p < .01$]. The RHD and control groups did not differ statistically.

3.2.3. Word–picture task

Scores for the LHD group (average accuracy = 81.02%, range = 32–100%; $S_E = 5.60$) were significantly lower than for the RHD group [average accuracy = 94.39%, range = 82–100%; $S_E = 1.43$; $t(32) = 2.23, p < .05$]. Both LHD and RHD groups scored significantly lower than the control group [average accuracy = 98.50%, range = 95.5–100%; $S_E = 0.95$; $t(21)_{LHD} = 3.00, p < .01$; $t(21)_{RHD} = 2.37, p < .05$].

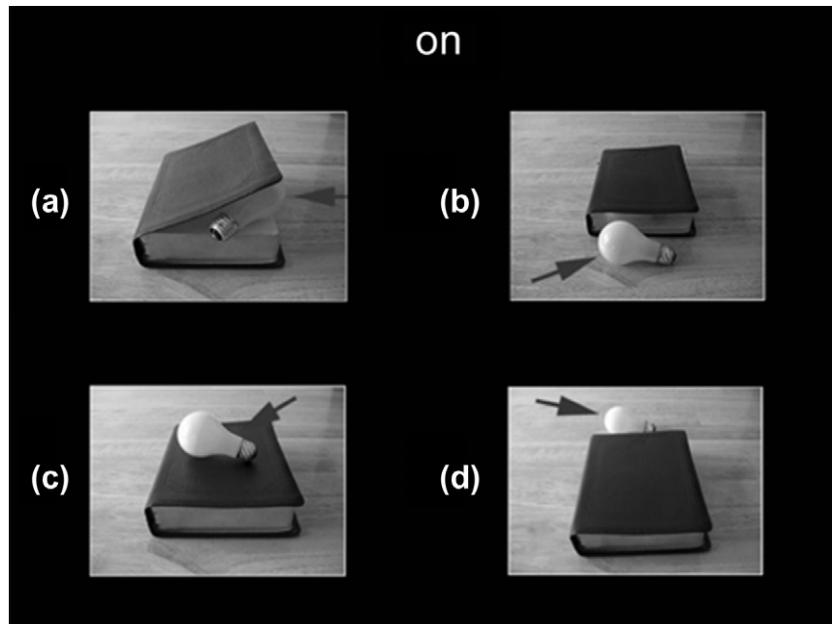


Fig. 6. Sample word–picture stimulus for *on*. Foils B (*in front of*) and D (*behind*) are across class foils belonging to the projective class. Foil A (*in*) is the within topological class foil and C is the correct answer. Original in color.

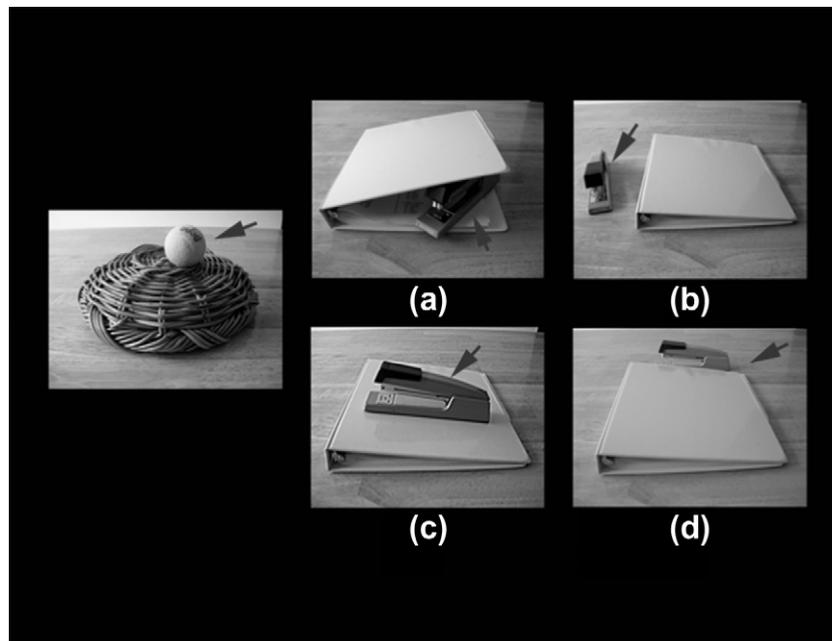


Fig. 7. Sample picture–picture stimulus for *on*. Foils B (*to the left of*) and B (*behind*) are across class foils belonging to the projective class. Foil A (*in*) is the within class foil and C is the correct answer. Original in color.

3.2.4. Picture–picture task

The LHD group (average accuracy = 74.87%, range = 23–95%; $S_E = 4.25$) was not significantly different from the RHD group (average accuracy = 80.75%, range = 68–95%; $S_E = 2.045$) but did score significantly lower than the control group [average accuracy = 87.12%, range = 72.7–100%; $S_E = 3.79$; $t(21) = 2.12$, $p < .05$]. The RHD group was not significantly different than the control.

The LHD group underperformed the RHD group across three of the four tasks, although LHD participants were significantly impaired relative to control groups on all matching tasks. Overall, the behavioral data suggest a left hemisphere bias for categorical spatial relational processing, whether tasks involve richly textured

images, schemas, or visually presented words. On a coarse hemispheric level, these data are consistent with theories that propose a left hemisphere advantage for encoding categorical spatial relations (Amorapanth et al., 2010; Kosslyn et al., 1989; Kosslyn, Thompson, Gitelman, & Alpert, 1998). For closer inspection of brain–behavior relations, we turn to the VLSM analyses.

3.3. VLSM analyses

Residual analyses are shown in Fig. 7c and d.

In order to (1) determine if the right and left hemispheres are differentially implicated in the representation of schematic

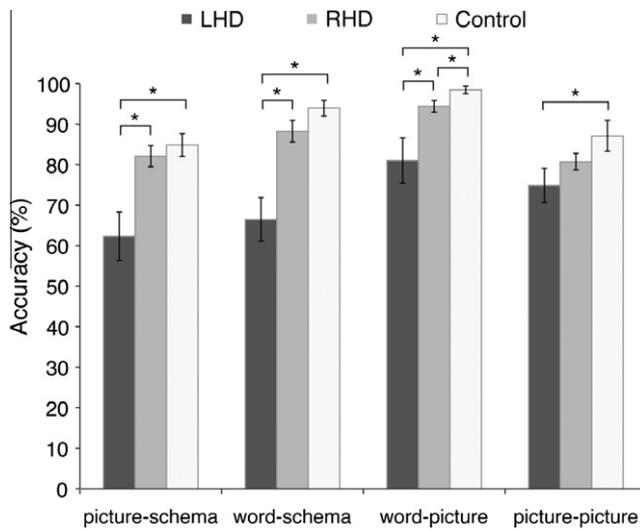


Fig. 8. Behavioral performance of left hemisphere damaged participants (LHD), right hemisphere damaged (RHD), and the control group on all tasks (picture–schema, word–schema, word–picture, and picture–picture matching tasks). Error bars denote S_E and asterisks significant p values according to independent sample t -tests.

information and (2) test the hypothesis that the hemispheres might differ in the extent to which they distinguish *between* kinds of non-linguistic spatial information, we report 4 residual analyses on 2 pairs of matching tasks.

We residualized tasks against each other in order to contrast particular representational formats (Amorapanth et al., 2010). By regressing performance for one matching task onto another and plotting the residual scores, we attempted to isolate behavioral variance associated with processing within a single representational format, or stimulus type (i.e., word, picture, or schema). For the most revealing residual analyses, matching tasks were paired in such a way that, relative to the other, each was composed of one unique and one common stimulus type. These pairings also ensured that all stimulus types were included in each analysis. With such paired comparisons, VLSM indicated the brain areas most critical for the representation of one stimulus type over another, between matching tasks. This is the case because VLSM residual analyses between two tasks not only indicate brain areas critical for unique processing in one task, but are also designed to remove the variability explained by processing common to both.

3.3.1. Residual analyses between verbal and analog formats

3.3.1.1. Word more than picture (*word–schema > picture–schema*).

The corrected t -statistic threshold with a significance level of $p = .05$ was 2.87 for the LHD group. There were no significant effects within the RHD group. The *word > picture* residual analysis identified voxels within the left middle frontal gyrus, premotor and primary motor cortex, superior temporal gyrus, and white matter undercutting the supramarginal gyrus that were significantly related with impaired processing of *word* stimuli compared to picture stimuli.

3.3.1.2. Picture more than word (*picture–schema > word–schema*).

The corrected t -statistic threshold with a significance level of $p = .05$ was 4.39 for the RHD group. There were no significant effects for the LHD group. The *picture > word* residual analysis found that lesions in the right inferior frontal, middle frontal, pre- and post-central gyri, and primary motor cortex are significantly correlated with impaired processing of *picture* stimuli compared to word stimuli.

3.3.2. Residual analyses within analog formats

3.3.2.1. Schema more than picture (*word–schema > word–picture*). There were no significant effects for the LHD group. The corrected t -statistic threshold with a significance level of $p = .05$ was 5.10 for the RHD group. The *schema > picture* residual analysis found that lesions in the supramarginal gyrus are significantly correlated with impaired processing on *schema* stimuli compared to picture stimuli.

3.3.2.2. Picture more than schema (*word–picture > word–schema*). There were no significant effects for RHD or LHD groups.

4. Discussion

4.1. Results summary

4.1.1. General

A total of 16 participants showed a general deficit across tasks (11 LHD patients; 5 RHD patients; See Table 1). LHD patients displayed significantly lower accuracy scores on 3 of the 4 tasks compared to RHD patients. These 3 tasks all included either words or schemas. In order to further investigate the precise contribution made by each hemisphere to task processing, we conducted residual analyses to partial out variance associated with a particular representational format. The results of the residual analyses suggest that verbal components of the matching tasks are processed in the left hemisphere (*word > picture*) and pictorial components in the right hemisphere (*picture > word*). They further suggest that the right hemisphere differentiates between distinct spatial formats (*schema > picture*). Below we discuss these results as organized by patient group in more detail.

4.1.2. Left hemisphere damage

We derived residual scores for both patient groups. Between-task VLSM residual analyses, such as those used in the present study, are designed to reveal brain areas critical for unique processing in one task, while factoring out variability in brain-behavior correlations explained by what is common to both (see above). With this logic in mind, particular residual analyses were carried out to isolate functionally distinct anatomical areas critical to task subcomponents. When contrasting performance on the two explicit schema tasks, a residual analysis (*word > picture*; Fig. 9c) found that damage to the left middle frontal, posterior and superior temporal gyri, premotor and primary motor cortex, and white matter undercutting the supramarginal gyrus is likely to produce impairment on *word* relative to picture processing, suggesting the importance these areas play in the verbal representation of lexicalized spatial relations. Overall, this result demonstrates that although both hemispheres participate in explicit schema processing, areas within the left hemisphere are biased to process discrete verbal representations over analog spatial representations.

Also of note, we did not find areas of critical damage within the left hemisphere correlating with deficits in the picture matching tasks that could not be accounted for by language deficits. This negative result at least raises the possibility that the left hemisphere bias for categorical spatial relations arises from deficits related to associating such discrete relations with verbal labels. Alternatively, the networks engaged by pictures of categorical spatial relations may be sufficiently intertwined with their linguistic representations that our methods are unable to distinguish the two empirically.

4.1.3. Right hemisphere damage

We performed a second residual analysis (*picture > word*; Fig. 9c) inverse to the one described above. Here we found that damage to the right middle and inferior frontal gyri, central gyrus

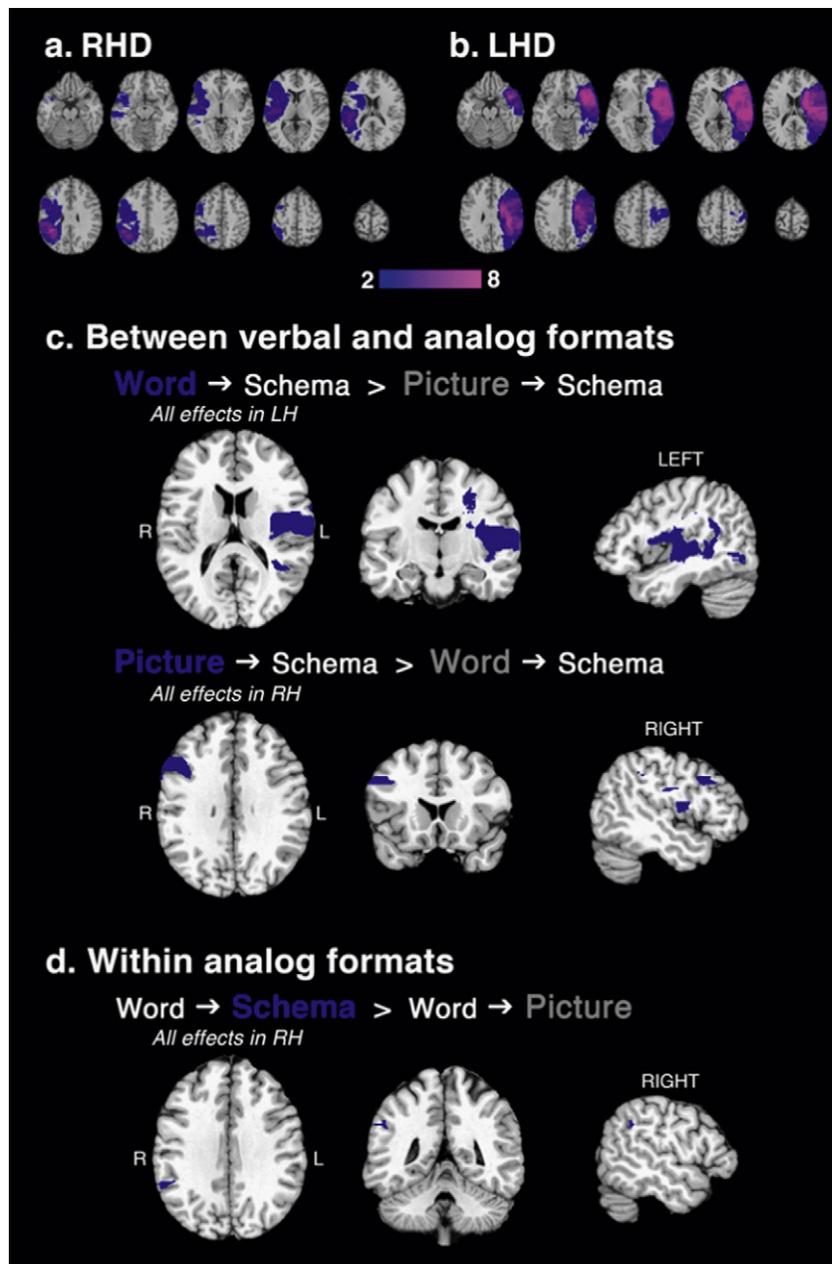


Fig. 9. RHD (a) and LHD (b) power maps for VLSM analyses. The number of overlapping lesions is illustrated by color, with blue denoting the fewest number of lesions at a particular voxel. Representative slices from VLSM residual analyses for (a) between format comparisons (*word* > *picture* in the LH and *picture* > *word* in the RH) and (b) within format comparisons (*schema* > *picture* in the RH). In the description of each analysis, the first task (to the left of the “>” sign) was regressed onto the second. Maps depict significant *t*-scores with a FDR of $q = 0.05$.

and primary motor cortex is likely to produce impairment on *picture* relative to *word* processing. This result suggests that these areas play an important role in the representation of spatial relations embedded in richly textured scenes. Residual analyses contrasting schema and picture matching tasks (*word*–*schema* and *word*–*picture* matching) further support the claim that the right hemisphere distinguishes between spatial formats. A residual analysis (*schema* > *picture*; Fig. 9d) found that damage to the supramarginal gyrus impaired *schema* relative to *picture* processing. Given that VLSM analyses both (1) showed that particular right hemisphere structures are predictive of behavioral impairment between tasks and (2) revealed, through residual analyses, fine tuned processing distinctions for different kinds of analog representations within the right hemisphere, the general view that only left hemisphere structures process categorical visuospatial information needs to be modified.

4.2. General discussion

Perhaps because schemas are simple and ubiquitous in the world, they are easy to take for granted. We commonly use such external, or *explicit* schemas when we read a map, obey traffic signs, or interpret graphs and diagrams. What makes schemas so simple to use is also what makes them so common across cultures, contexts, and academic disciplines. When people produce or use schematic figures in an explicit manner, a small set of basic spatial forms provides enough structure to convey discrete meanings. Configurations of circles and lines in space can describe complex relations among a wide array of concrete or abstract entities that will be understood by the majority of people. At the most fundamental level of schematic representation, lines stand for barriers or surfaces, circles stand for enclosed spaces, and arrows stand for paths (Tversky, Zacks, Lee, & Heiser, 2000). According to such

a view, these core meanings are not arbitrary. Rather, the abstracted forms themselves suggest the meaning of the primitive spatial concept they aim to represent: a spatial “vocabulary,” or core set of conceptual primitives that underlies our use of schemas.

An interesting question concerns the extent to which the brain codes such spatial relations in an analogous format. That is, can the meanings of abstract concepts be represented without language-like mental structures? Although the answer to this question may be less intuitive, it appears that such meaning can be stored and processed independent of verbal representations (i.e., independent of phonological or orthographic representations). Infants are able to extract the kinds of spatial relational categories relevant to theories of schematic mental representation before they understand words for such categories. Preverbal infants younger than 5 months-old demonstrate understanding for containment and support relations (Aguilar & Baillargeon, 1998; Baillargeon, 1994; Needham & Baillargeon, 1993), above and below (Quinn, Cummins, Kase, Martin, & Weissman, 1996), and the ability to abstract, and discriminate between, the distinct paths of moving objects (Pruden, Hirsh-Pasek, Maguire, & Meyer, 2004). That is, well before they are able to use lexicalized spatial prepositions like IN, ON, ABOVE, and THROUGH, infants appear to understand the abstract spatial meanings suggested by each. While the kinds of primitive spatial concepts understood by both adult map-readers and preverbal infants are often lexicalized by prepositions, 9 month-old infants raised in English-speaking homes can even extract spatial relational contrasts that are not lexicalized in their native language environment (McDonough, Choi, & Mandler, 2003). Infant spatial abilities demonstrate that spatial meaning can be extracted from complex spatial arrays without the aid of verbal labels, and further suggests the useful role nonverbal, but abstract representations might play in mediating between perception and language.

Along these lines, it has been theorized that schematic representations provide the *implicit* foundation for abstract semantic concepts (Chatterjee, 2001; Jackendoff, 1996; Johnson, 1987; Lakoff & Johnson, 1999; Mandler, 1996; Talmy, 2000). For example, Johnson (1987) proposes that abstract cognitive schemas serve to mediate between sense percepts and propositional structures. Jackendoff (1996) suggests that complex spatial events are broken down and represented as primitive elements like “movement,” “path,” and “location.” And Mandler (1996) describes a framework for infant conceptual development in which schemas dynamically “re-describe” generalized spatial and movement patterns. *Image schema* theories further suggest that such primitive semantic representations serve as a foundation upon which more complex conceptual structures are built. According to some of these theories, primitive spatial schemas allow us to think and talk about more abstract conceptual categories like time, emotions and morality (Johnson, 1987; Lakoff & Johnson, 1999).

We were interested in a schema’s primary function—the same one that appears to operate during infancy. That is, we were interested in understanding the neural organization underlying our use of spatial schemas when thinking about space. Considering the intermediate representational status of schemas, and that previous studies investigating locative spatial relations have implicated both left and right hemisphere neural structures (e.g., Damasio et al., 2001; Kemmerer & Tranel, 2000; Tranel & Kemmerer, 2004) we wished to determine how schematic representations of categorical relations might be related to verbal descriptors on the one hand, and to richly textured perceptual representations on the other.

Although the current study does not refute the general notion of a left hemisphere bias towards processing prepositions, our results suggest that right hemisphere structures play a critical role in representing categorical spatial relations in nonverbal formats. Some previous work supports this general finding; evidence for a left hemisphere role in representing spatial relations for purposes of

language and a right hemisphere role in categorical visuospatial processing has been found. For example, a PET study that used schematic abstract line drawings (Damasio et al., 2001) found significant right supramarginal gyrus activation in a subtraction of (A) naming spatial relations between difficult-to-name abstract shapes and (B) naming spatial relations between concrete tools and utensils. Kemmerer and Tranel (2000) found a double dissociation between linguistic and perceptual representations of spatial relations when the performance of two patients with left or right hemisphere damage was compared across verbal and spatial tasks. The patient with left fronto-parietal damage did poorly on tasks relying on categorical representations encoded by prepositions while displaying relatively intact performance on the visuospatial tasks. The patient with damage to right frontal, parietal, and temporal areas displayed intact performance on language tasks, but displayed impairments on the visuospatial tasks. Interestingly, this study used traditional visuospatial tasks (Hooper visual organization test; Taylor complex figure test; Benton three-dimensional block construction test), which arguably do not lend themselves easily to verbal strategies, as a means of assessing the perceptual component of the double dissociation. In a follow-up study (Tranel & Kemmerer, 2004) they found that of the participants who performed within the normal range on traditional visuospatial tasks, only the left hemisphere damaged subjects had deficits in naming tasks and matching tasks using nonverbal stimuli based on lexicalized locative relations.

The simple meanings of prepositions when used to describe concrete spatial relations presented the prospect of investigating the structure of the semantic system in a particularly stark form. We investigated the neural basis of spatial semantics by distinguishing between those meanings associated with (1) phonological and orthographic representations, or *words*, (2) richly textured images or *pictures*, and (3) simplified abstract images or *schemas*. These schemas serve as intermediate structures between words and the rich perceptual scenes present in the world. One can summarize our findings by saying that these systems appear to be intertwined both functionally and anatomically. The left hemisphere does seem to be biased to process these kinds of categorical spatial relations. However, we find no evidence that the left hemisphere distinguishes between different kinds of analog representations. Furthermore, categorical spatial representation deficits in the left hemisphere are difficult to distinguish from deficits associated with labeling these relations verbally.

The observations from our left-brain damaged participants should not be taken to infer that perceiving categorical spatial relations in humans is solely a function of the ability to name them. Data from our right-brain damaged participants makes clear that deficits in these analog categorical spatial relations do occur with right brain damage, and that these deficits cannot be accounted for by naming deficits. In addition, the right hemisphere distinguishes between different kinds of analog spatial representations (schemas vs. pictures). This result suggests that the right hemisphere plays a special role in extracting schematic representations from pictorial ones.

The evidence we found for the representation of distinguishable forms of nonverbal spatial relational information in the right hemisphere also suggests that abstract meanings can be stored independently of left hemisphere verbal representations. The fact that the right hemisphere can make fine-tuned distinctions between different kinds of nonverbal abstract categorical spatial representations further suggests that image schema theories may provide a valid construct for understanding how primitive meanings can be represented without language. This is not to say that implicit image schemas are necessarily represented in the brain like explicit schemas. Rather, the evidence for the right hemisphere’s ability to abstract and store such spatial relations independent of language suggests that image schemas could represent prototypical spatial categories in preverbal infants.

The pattern of results from the task and residual analyses suggests that the right hemisphere also instantiates these analog representations distinctly, whether they be richly textured representations or skeletal schematic representations. Although it is almost certainly an oversimplification, understanding the brain in terms of such a—DIGITAL-LEFT|ANALOG-RIGHT—functional-hemispheric divide might help illuminate issues regarding how linguistic and spatial processing are related to one another, at least with respect to the underlying neural basis for the kinds of spatial relations lexicalized by prepositions. According to the present study, it appears that the left hemisphere bias, often found for processing categorical relations, is integrally related to verbal labeling; and that the right hemisphere represents categorical spatial meanings in nonverbal formats. The right supramarginal gyrus may play a privileged role in processing analog spatial relations, by extracting their schematic structure. This region probably works in concert with the left hemisphere regions processing words to distill and abstract static spatial relations from the richly textured world in which such relations are embedded.

Our findings are consistent with the general view that verbal, conceptual, and perceptual representations share a parallel structure in the brain (Chatterjee, 2008) and further suggest the organization of a neural system capable of representing meaning without language. The idea that abstract yet discrete meanings can be represented without language is a provocative idea, with implications that extend beyond the populations investigated in the present study. Research in other fields—especially developmental psychology—suggests that verbal representations are not essential to representing abstract semantics in a more general sense. Although image schema theories are well developed in other literatures, providing a theoretically plausible mechanism for representing meaning without language, there is little empirical evidence to support their existence in the brain. We hope the current study will inspire more work in this neglected area of research.

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