

The Schematic Representation of Spatial Relations: Evidence from Group and Single-Case Lesion Studies

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Abstract

To what extent are schematic representations neurally distinguished from language on the one hand, and from rich perceptual representations on the other? In a group lesion study, matching tasks depicting categorical spatial relations were used to probe for the comprehension of basic spatial concepts across distinct representational formats (words, pictures, schemas). Focused residual analyses using voxel-based lesion-symptom mapping (VLSM) suggest that left hemisphere deficits in categorical spatial representation are difficult to distinguish from deficits in naming such relations, and that the right hemisphere plays a special role in extracting schematic representations from richly textured pictures. EE555, a patient with simultagnosia, performed six similar matching tasks. On the only two tasks that did not include matching to, or from, schemas, EE555 performed at chance levels. EE555 was significantly better on schema tasks, indicating that abstract analog representations make spatial relations visible in a manner that symbols and complex images do not.

Keywords: schemas; spatial relations; vlsm; case studies

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. A place to start could involve observing how abstract semantic information is intentionally transmitted without either the aid of words or rich imagery. Abstract graphics have been used to convey such meanings long before humans kept formal history. Map-like cave drawings, rendered over 6,000 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 (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 some level of 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, like 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 a theoretically intermediate position between abstract words and concrete percepts in a graded model of representation (A Chatterjee, 2001; A. Chatterjee, 2010; Kranjec & Chatterjee, 2010). 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. We are interested in understanding whether the brain distinguishes between paired-down, externalized depictions of spatial schemas from other information formats like words and pictures.

Perhaps because schemas are simple and ubiquitous, they are easy to take for granted. We commonly use such external, or explicit schemas when we find the appropriate restroom, 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). These core meanings are not arbitrary. Rather, the abstracted forms themselves suggest the meaning of the primitive spatial concept they aim to represent. This universal spatial “vocabulary” suggests that a core set of conceptual primitives underlies our use of schemas.

But can the meanings of abstract concepts be processed without language-dependent *mental* representations? While a good deal about spatial schemas has been written within cognitive linguistics (Lakoff & Johnson, 1999; Mandler, 1992; Talmy, 2000), 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 Friederici (Frederici, 1981) demonstrated that Wernicke aphasics have impairments in processing locative prepositions. Landau and Jackendoff (1993) subsequently proposed that 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 et al. (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 et al. (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.

The current investigation concerns the neural organization underlying our use of spatial schemas when thinking about space. We are interested in how we access spatial meanings—like we do 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 schemas. The current study attempts to distinguish between those brain areas responsible for representing spatial relations in (1) rich perceptual detail, (2) an intermediate level of schematic abstraction as described above and (3) 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.

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, Waller, & Chatterjee, 2007).

The main hypotheses being tested in Experiment 1 concern the extent to which the left or right hemisphere show 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—suggest that either of the above principles of neural organization could be the case. We sought to test the validity of these two alternative hypotheses. Experiment 2 then investigates whether such intermediate forms of representation, because of their possible role in linking language and perception, might facilitate comprehension in a patient with severe spatio-visual deficits.

Stimuli

Word and Picture Selection

We selected four prepositions to serve as the **words** in our matching tasks according to two main preposition classes described in the literature (Talmy, 2000). Most simply: *topologic* prepositions describe figure-ground relations that vary along the dimensions of contact and degree of enclosure, (i.e. IN and ON); and *projective* prepositions, describe figure-ground relations that vary along the dimensions of vertical or horizontal displacement (i.e. ABOVE and BELOW). Each matching task used these 4 spatial concepts.

For the **pictures** in our matching tasks, we used realistic color image stimuli. The selected pictures were designed to unambiguously depict the same spatial relations as denoted by the prepositions. 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.

We constructed **schemas** consisting of simple lines and geometric forms using graphic-making tools in Photoshop. The set of four schemas varied along parameters proposed by Talmy (2000), such as containment, support, and degree of separation.

The particular stimuli used in Experiments 1 and 2 differed although their structure was essentially identical.

Experiment 1: Group Study (VLSM)

Participants

17 right hemisphere damaged (RHD) and 17 left hemisphere damaged (LHD) patients ranging from 48-85 years of age

(RHD: mean = 60.4; LHD: mean = 60.9) with chronic lesions (of at least six months duration) were recruited from the Focal Lesion Patient Database (Center for Cognitive Neuroscience, University of Pennsylvania). 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.

Procedure

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. See Figures 1A-D. In Experiment 1, 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 spatial probes representing topological relations (IN or ON) and two representing projective relations (ABOVE or BELOW).

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. (Fig. 1A) 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. 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.

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 (Figure 1B).

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 (Figure 1C).

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 (Figure 1D).

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. The t-map for each analysis was thresholded to control the False Discovery Rate (FDR) at $q = 0.05$. The procedure allows us to identify 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.

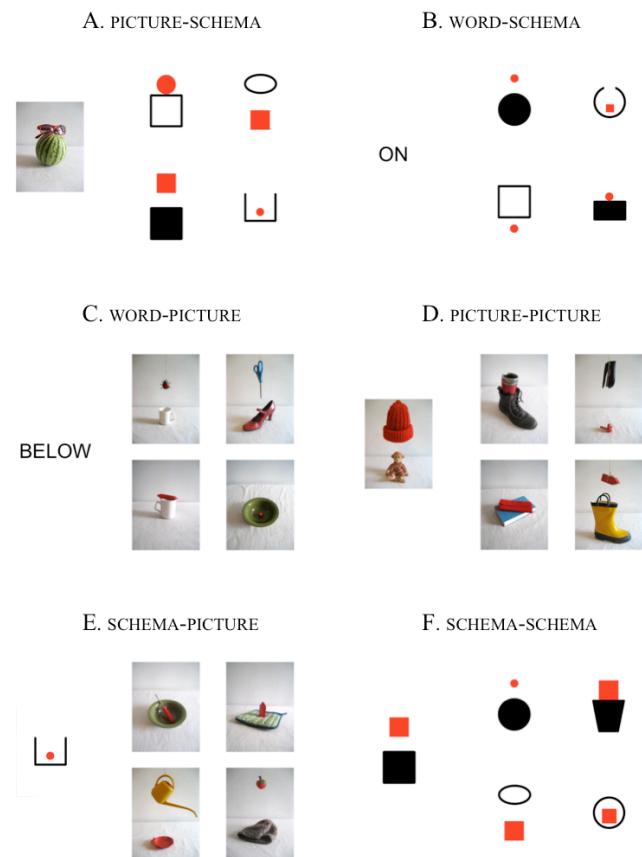


Figure 1: Types of matching tasks. (Group Study 1A-D; Case Study 1A-F)

We incorporate residual analyses as part of our approach to using VLSM to orthogonalize task processing (Amorapanth et al., 2010). When performances across two tasks are correlated, one can use VLSM to probe for divergent brain-behavior correlations across the two tasks.

By correlating the residual scores (of one task itself correlated on another) with voxel damage, one can assess regions of vulnerability for that task that cannot be accounted for by vulnerability to the other task.

Behavioral Results

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%; $S_E=2.60$; $t(32) = 2.93, p < .01$].

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%; $S_E = 2.65$; $t(32) = 3.47, p < .01$].

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%; $S_E = 1.43$; $t(32) = 2.23, p < .05$].

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%; $S_E = 2.045$)

Residual VLSM analyses

Residual analyses are shown in Figures 2c and 2d. By design, for VLSM methods, greater behavioral variability within groups is desirable to identify specific brain behavior correlations. This greater behavioral variability within each group maximizes the likelihood of finding statistically robust differences within the group and minimizes the likelihood of finding differences across groups.

In order to (1) determine if the right and left hemispheres are differentially implicated in the representation of schematic 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 conducted 3 residual analyses on 2 pairs of matching tasks.

We residualized tasks against each other in order to establish orthogonal measures for 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.

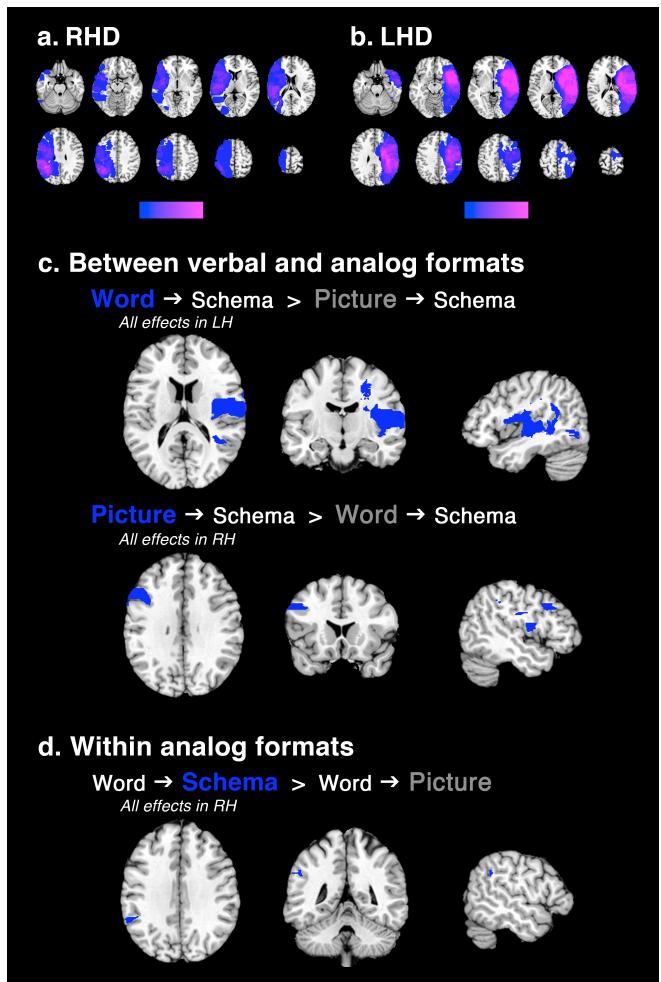


Figure 2: VLSM. (Lesion overlap 2A, B; Results 2C, D)

Word more than Picture (Word-Schema > Picture-Schema) The corrected t-statistic threshold with a significance level of $p = .05$ was 2.87112 for the LHD group. There were no significant effects within the RHD group. The word > picture residual analysis found that lesions to the left middle frontal gyrus, premotor and primary motor cortex, superior temporal gyrus and white matter undercutting the supramarginal gyrus are significantly correlated with impaired processing of *word* stimuli compared to *picture* stimuli. (Figure 2c [top].)

Picture more than Word (Picture-Schema > Word-Schema) The corrected t-statistic threshold with a significance level of $p = .05$ was 4.38983 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, middle frontal and central gyri, and primary motor cortex are significantly correlated with impaired processing of *picture* stimuli compared to word stimuli. (Figure 2c [bottom].)

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 5.09678 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. (Figure 2d.)

Results Summary 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).

Experiment 2: Single Case Study

Simultagnosia presents an interesting case for the investigation of schemas. If schemas help us to abstract spatial relations from complex scenes, and aid relational thinking, perhaps they might be especially helpful for an individual with simultagnosia.

Participants

Patient EE555 (43 years old, 18 years education) experienced three parietal lobe infarcts between May and June of 2004. These events resulted in bilateral lesions extending from the occipital lobes to middle parts of the inferior parietal sulcus. Behavioral testing indicated simultagnosia. EE555 was unable to comprehend more than a one object simultaneously 30 months after her most recent stroke. For example, she showed a complete local bias with Navon Letters. (Berryhill, Fendrich, & Olson, 2009). An age and education matched control group also participated (N=5; mean_{age}=51.4 years, mean_{education}=17 years).

Procedure

Spatial matching tasks The design of the case study was very similar to that of the group study, however, in addition to word-schema, picture-schema, word-picture, and picture-picture matching tasks, EE555 and controls also performed two additional matching tasks: schema-word, and schema-schema (Fig1A-F). Each task consisted of 80 trials.

Results

Controls outperformed EE555 on all tasks [p 's <.01 (Crawford & Garthwaite, 2007)]. On the two tasks that did not include matching to, or from, schemas (word-to-picture [W-P]; picture-to-picture [P-P]) EE555 performed at chance levels (20% and 25%, respectively; χ^2 , p 's > .3). For the

tasks with schemas (schema-to-picture [S-P]; word-to-schema [W-S]; schema-to-schema [S-S]; picture-to-schema [P-S]) performance was significantly better than chance (50%, 74%, 67%, 84% respectively, χ^2 , p 's < .01). Accuracy results are summarized in Figure 3.

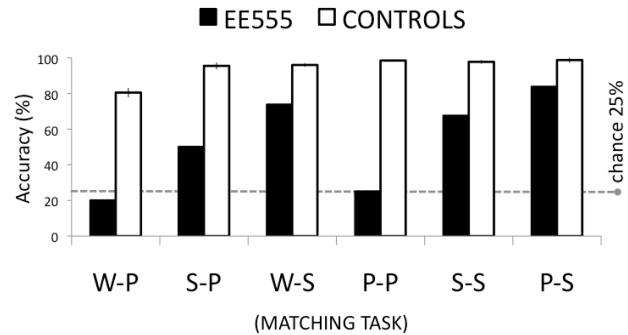


Figure 3: Accuracy across all tasks for EE555 and controls.

Schemas appear to make spatial relations visible for a patient with simultagnosia. These results provide general insight as to how schemas facilitate spatial reasoning when used in graphic depictions, and how such theoretically intermediate representational structures could serve to link perceptual and verbal representations of spatial relations in the brain. It is our position that, (1) schemas are intermediate representational structures that link pictures and words; that they (2) preserve analog qualities like pictures, but may be particularly useful, especially for an individual with simultagnosia, because they may be (3) processed more holistically like symbols

General Discussion

Simplified schematic representations appear ubiquitously in maps and diagrams. Yet, little is known about the neural instantiation of these important communicative devices. We were interested in understanding the neural organization for schematic representations of spatial relations. Considering the intermediate representational status of schemas, and that previous studies investigating locative spatial relations have implicated both left and right hemisphere neural structures, 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.

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 rich perceptual scenes. 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 In Experiment 1 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. The results of Experiment 2, suggest that the content of schematic representations can bring spatial meaning to awareness in a way that words by themselves cannot.

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