Lateralization of Categorical and Coordinate Spatial Functions: A Study of Unilateral Stroke Patients

Bruno Laeng
University of Michigan

Abstract

■ Sixty patients with unilateral stroke (half with left hemisphere damage and half with right hemisphere damage) and a control group ($N = 15$) matched for age and educational level were tested in two experiments. In one experiment they were first shown, on each trial, a sample drawing depicting one or more objects. Following a short delay, they were asked to identify the drawing when it was paired with a drawing in which the same object(s) was transformed in categorical or coordinate spatial relations. In the other experiment, the same subjects first were shown, on each trial, a sample drawing. They then judged which of two variants (each in one type of spatial relation) looked more similar to the sample drawing. Typically, patients with left-sided stroke mistakenly identified the categorical transformation for the sample drawing in the first task; in the second task, they judged the categorical transformation as more similar to the sample drawing. Patients with right-sided stroke mistakenly identified the coordinate transformations for the sample drawing in the first task, and, in the second task, typically judged the drawings transformed along coordinate spatial relations as more similar to the sample drawing. These findings provide evidence for complementary lateralization of the two types of spatial perception. It can therefore be inferred that separate functional subsystems process the two types of spatial relations. ■

INTRODUCTION

It is intuitively apparent that objects in the visual scene can be judged as being in specific spatial relations to each other, quite apart from information about their precise location. These spatial relations are usually expressed by verbal prepositions such as in, on, behind, or simple phrases such as to the left, attached to. The actual spatial distance is not made explicit in such terms, and it is in fact irrelevant. It has been hypothesized that these verbal terms are based upon perceptions characterized as "categorical" (Kosslyn, 1987), which describe general properties of objects in space without encoding their specific absolute position. An object is assigned to a broad equivalence class of spatial positions. For instance, an object can be described as to the left of another, even though their locations may vary considerably with respect to the vertical and horizontal axes.

To move about efficiently in our physical environment and to manipulate objects, we also need to be informed of the precise location of objects and the actual distance between them. These types of representations are called "coordinate" (Kosslyn, 1987), because location can be explicitly specified in units of component axes of the spatial framework.

On the basis of theoretical considerations, computer simulations and a look at the neuropsychological literature, Kosslyn has proposed a theory of brain organization (Kosslyn, 1987; Kosslyn, Koenig, Barrett, Cave, Tang, & Gabrieli, 1989; Kosslyn & Koenig, 1992) positing separate and complementarily lateralized cerebral components for the encoding and processing of each spatial relation. More specifically, the neural substrate underlying the perception of categorical relations would be contained mainly within the the left hemisphere, whereas for coordinate relations the substrate would be mainly within the right hemisphere.

Some predictions necessarily follow from the above described theory: A breakdown of categorical function would be expected after left-sided lesions and such a deficit would be characterized by an inability to recognize violations of equivalencies among members of a class of categorical spatial relations; in contrast, right-sided lesions would cause a breakdown of coordinate function, this deficit being characterized by an inability to evaluate differences in the coordinate metrics (like specific distance, size, and orientation) of objects and their spatial relations.

The study presented here offers some evidence that lesions due to stroke in the posterior areas of the human

© 1994 Massachusetts Institute of Technology

brain will result in specific deficits or impairments in one or the other of the two types of spatial relations depending on which side has been affected by the lesion. Tasks that differed in terms of categorical and coordinate relations were constructed. The underlying hypothesis was that patients with lesions in the posterior regions of one hemisphere should become particularly "insensitive" to changes in the spatial relations for which it is specialized.

Some spatial categories that we assume to be universal were selected in order to test specifically for an impairment in categorical spatial relations. All Indo-European languages specify in analogous terms the spatial attributes of objects (Miller & Johnson-Laird, 1976, p. 375). In the English language, a whole grammatical class—prepositions—is almost completely devoted to expressing spatial relations (Clark, 1973; Landau & Jackendoff, 1993).

Coordinate representations are needed for more precise information about positions. These coordinate aspects can also be put into language. However, this is a relatively recent acquisition in human culture, and constitutes almost exclusively the language of science and technology. There is, in fact, a substantial difference in our capacity to judge and put into words whether an object is in a specific categorical spatial relation with another (e.g., one inside the other) as opposed to our capacity to evaluate and put into words metric aspects, like the size, length, or volume of objects or their distances in metric units. It seems that although in principle we have a vocabulary that would allow us to express any metric value precisely, and ease to experience and differentiate objects of varying sizes and lengths, such information seems to be not readily available to our language system despite the clarity of our visual experience (Kosslyn & Koenig, 1993; Landau & Jackendoff, 1993). On the contrary, naming categorical relations is a relatively easy task and constitutes the way we usually talk about space.

To test the hemispheric specialization for the two types of spatial representations, memory tasks of the matching-to-sample kind were used, since a memory task is more likely to expose laterality effects than a perceptual matching task (Moscovitch, 1979). Perceptual tasks are also less preferable than memory tasks, since the simultaneous presentation of the stimuli in the perceptual tasks may allow the subject to utilize other perceptual cues (e.g., differences in contour) or develop strategies (e.g., comparing patterns of eye movements when visually inspecting the stimuli) that may lead to the recognition of differences in the stimuli regardless of the patients' inability in encoding specific spatial relations. Additionally, one reason for using a matching task is that it reduces the intervention of language processes, both in comprehension and expression, that are commonly disturbed in patients with left hemisphere lesions.

In one task ("identity test"), left-sided (LH) and right-sided (RH) stroke patients and matched control subjects were shown color drawings representing one or more objects. Most of the objects depicted in the drawings were animals, but common objects and abstract figures were also included. After the presentation of the drawing and following a short delay, the subjects were shown the same drawing again together with an alternative drawing in which the same object(s) had undergone some transformations in one type of spatial relation (see Fig. 1A and B, for some examples). The subjects were asked to indicate which drawing was identical to the one seen first. In half of the items the original drawing would show a change in some categorical relation without a change in the coordinate relations *between* the objects (e.g., if the original drawing showed two cats, one giving a specific side to another, the variant may show a change in the way the cats' sides relate to each other, while the distance between the two cats is kept unvaried). The other half of the items, however, would show a variation along metric coordinates while keeping the original categorical relations unchanged (e.g., the distance on the horizontal plane between the two cats may now be stretched or compressed, which does not cause a violation of any class of categorical descriptions between the two animals).

It was predicted that left-sided stroke patients would mistakenly recognize the categorical transformations as identical to the original sample, whereas right-sided stroke patients would mistakenly recognize the drawing that had been transformed along coordinate spatial relations as identical to the original sample.

Since in the previous experiment it is possible that a subject may respond correctly despite the fact that the unilateral lesion "weakened" one perceptual subsytem relative to the other, another task ("similarity test") that may be more sensitive than an identification task was also performed. In this test, the same patients and control subjects were shown a drawing representing one or more objects and then shortly afterward asked to evaluate which of two other drawings [where one alternative showed the same object(s) after having undergone some transformations in categorical spatial relations, and the other alternative in coordinate spatial relations] "looked more similar" (see Fig. 1C and D for some examples). If an imbalance in relative efficiency of the two representational subsystems occurred, then a shift of preference or similarity judgments should be observed in this test, since, supposedly, the two subsystems are pitted one against the other and their relative "strengths" brought to the surface.

It was then predicted that LH patients would find the categorically transformed representation to be similar more often than RH patients and control subjects would, whereas RH patients would "see" the representation transformed along categorical spatial relations as more similar less frequently than the control subjects would.

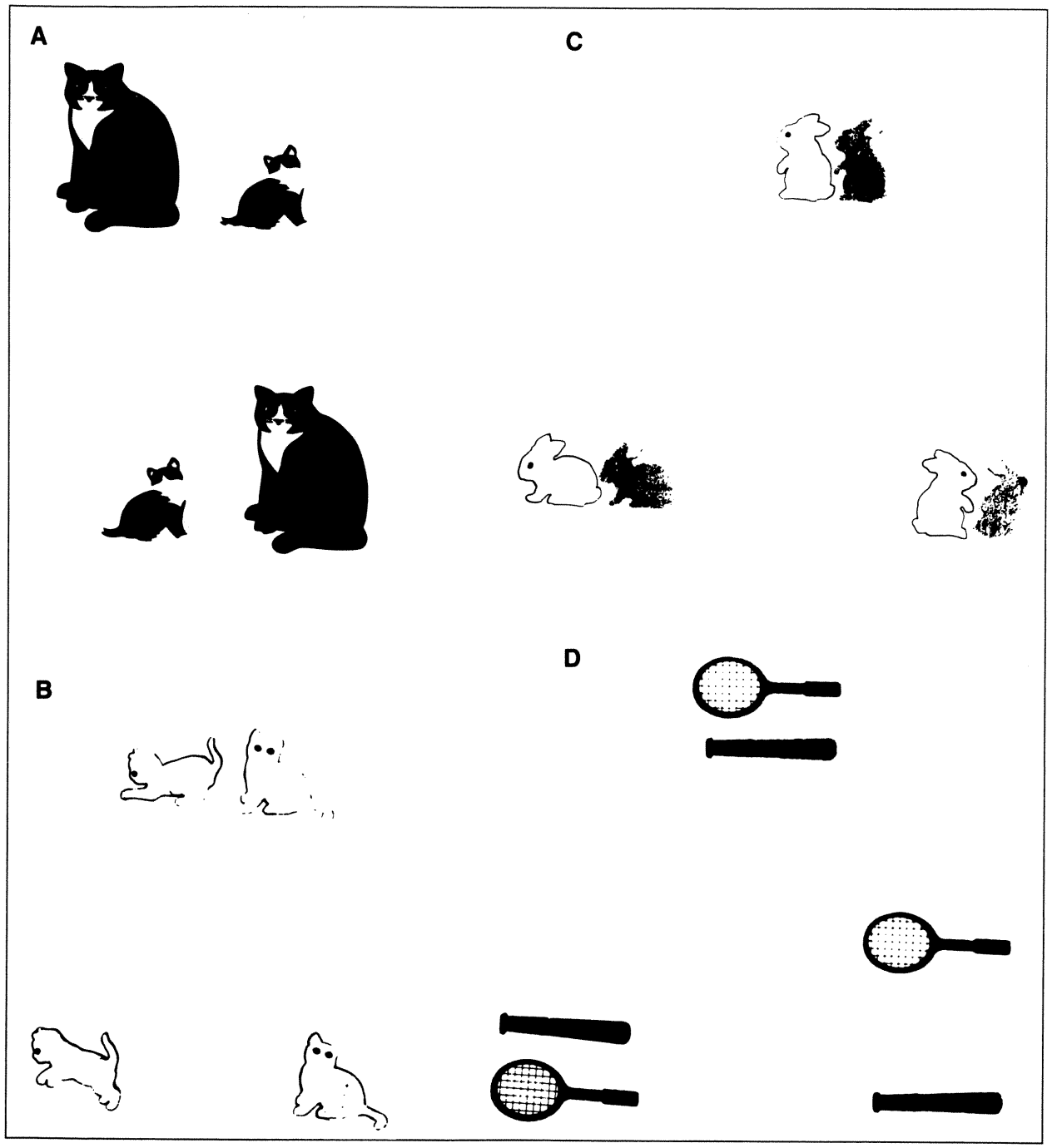

Figure 1. Examples of drawings in the identity test (A, B) and similarity test (C, D).

RESULTS

Identity Test

A "categorical" error was defined by a subject's choice, during the matching portion of each trial, of the categorical variant instead of the sample figure; a "coordinate" errror was defined by choice of the coordinate variant.

LH patients made more categorical errors (mean = 3.17; SE = 0.38) than coordinate errors (mean = 1.77; SE = 0.27). In contrast, RH patients made more coordinate errors (mean = 2.83; SE = 0.28) than categorical errors (mean = 1.80; SE = 0.33). Normal subjects made more coordinate errors (mean = 1.20; SE = 0.28) than categorical errors (mean = 0.73; SE = 0.15).

A repeated-measures ANOVA of total errors, with le-

sion (left/right/none) as the between-subjects factor and spatial relation (categorical/coordinate) as the within-subjects factor, revealed a significant main effect of lesion [$F(2, 72) = 7.70; p < 0.0009$] and a significant interaction of the lesion and spatial relation factors [F (2, 72) = 11.66; $p < 0.0001$]. The main effect was clearly due to the smaller number of errors committed by the normal subjects (mean = 0.97; SE = 0.16), as opposed to those committed by the LH patients (mean = 2.47; SE = 0.25) and the RH patients (mean = 2.32; SE = 0.23). A post hoc comparison with the Scheffe's test showed that normal subjects made significantly fewer errors than the left-sided lesion group ($p < 0.0015$) or the right-sided lesion group ($p < 0.0002$), whereas the two lesion groups did not differ significantly from each other in overall number of errors ($p < 0.76$).

The significant interaction of lesion and spatial relation (see Fig. 2) demonstrates that the two groups of patients differed in the kind of errors they made. As predicted, LH patients made on average more categorical errors than RH patients [$t(58) = 2.70; p < 0.004$]. Also, the prediction that patients in the RH group would make on average more coordinate errors than patients in the LH group was confirmed [$t(58) = 2.74; p < 0.004$].

As predicted, RH patients made significantly more coordinate errors than categorical errors [$t(29) = 2.89; p < 0.004$] and more coordinate errors than the normal subjects did [$t(43) = 3.64; p < 0.0003$]. The normal subjects' tendency to make more coordinate errors than categorical errors (see Fig. 3) was not significant [$t(14) = 1.38$; n.s.]. As predicted, LH patients made significantly more categorical than coordinate errors [$t(29) = 3.32; p < 0.001$], and more categorical errors than the normal subjects [$t(43) = 4.37; p < 0.0001$].

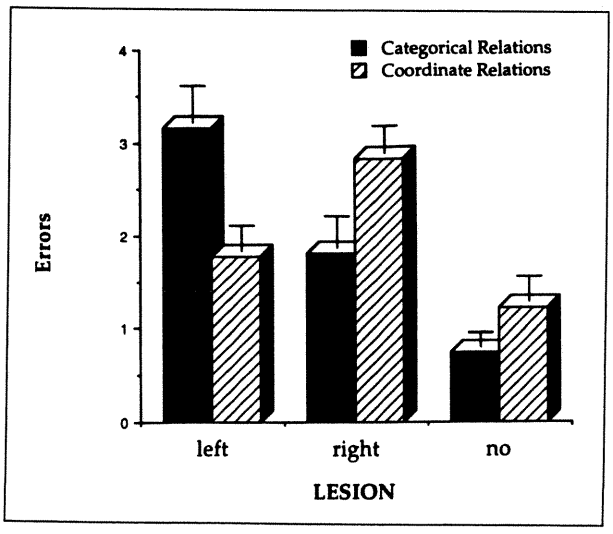

Figure 2. Identity test. Mean and standard error of numbers of errors in each lesion group (left, right, no) for items with transformations in categorical or coordinate spatial relations.

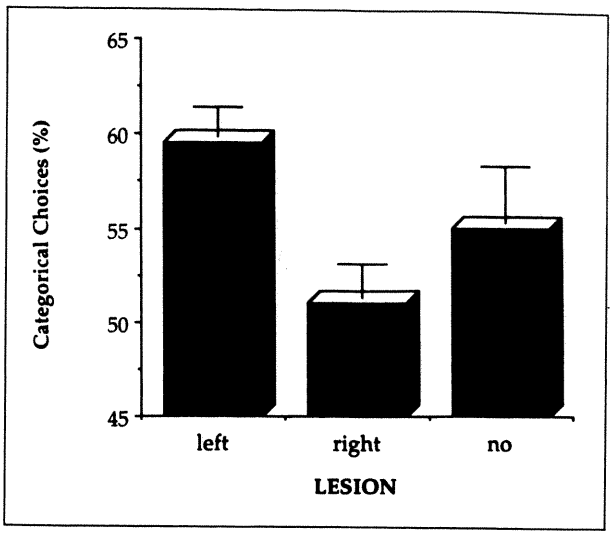

Figure 3. Similarity test. Mean and standard error of number of choices of match drawings with transformations in categorical spatial relations for each lesion group (left, right, no).

The number of coordinate errors made by LH patients was not significantly different from the normal performance [$t(43) = 1.33$; n.s.]. However, RH patients differed from normal performance also in their number of categorical errors [$t(43) = 2.22; p < 0.016$].

Similarity Test

A "categorical" choice was defined by a subject's choosing, during the matching portion of each trial, the categorical variant, whereas a "coordinate" choice was defined by choosing the coordinate variant. Figure 3 shows the percentage of categorical choices for each group of subjects (a 50% score indicated that the subject chose as similar to the sample a categorical variant as often as the coordinate variant).

All groups of subjects tended to choose the categorical match as the more similar to the original sample. However, LH patients made more categorical choices (mean = 59.55; SE = 1.52) than did the control subjects (mean = 55.00; SE = 2.91), who, in turn made more categorical choices than the RH patients did (mean = 51.03; SE = 1.79).

A repeated-measures ANOVA, with lesion (left/right/none) as the between-subjects factor and number of choices of the categorical match as the dependent variable revealed a significant main effect of lesion [$F(2, 69) = 5.79; p < 0.004$]. A post hoc comparison with Scheffe's test showed that the LH patients differed significantly from the RH patients ($p < 0.004$), whereas the normal subjects did not differ significantly in their number of categorical choices from either the LH patients ($p < 0.32$) or the RH patients ($p < 0.42$).

Correlation Between the Two Tests and Effect Sizes

The difference between percent categorical errors/choices and coordinate errors/choices was computed for each test and for each subject. A simple correlation analysis was then performed that revealed a slight but positive correlation between the two tests [$r = 0.21$; $F(1/70) = 3.340; p < 0.07$].

Effect size measures were also obtained for each test. For the interaction between the lesion factor (left/right/none) and the spatial relation factor (categorical/coordinate) in the identity test, $\eta^2 = 0.25$ and power = 0.99. For the effect of lesion (left/right/none) in the similarity test $\eta^2 = 0.16$ and power = 0.90. Although the variance in performance accounted for by the effect of unilateral damage seems to be in the "small" range (Cohen, 1977), it is important to note that in the case of the identity test, only 10 items comprised each spatial relation condition and, nevertheless, an appreciable effect size could be revealed.

Site of Lesion

Patients with lesions affecting the parietal lobe only, parietal and temporal lobes, and parietal and frontal lobes were included in separate repeated-measures ANOVAs. Each included the side of lesion as between-subjects factor, spatial relations as the within-subjects factor, and number of errors in the identity test or number of categorical choices in the similarity test as the dependent variable. The reason for excluding patients ($N = 18$) with lesions other than in the categories described above was that their numbers in additional region categories would have been smaller than five (see Table 1).

Identity Test

As shown in Figure 4A, which represents the difference between categorical and coordinate errors, LH patients grouped for lesion site showed a higher incidence of categorical errors, whereas RH grouped for site of lesion showed a higher incidence of coordinate errors. However, this effect appeared more pronounced in the "parietal only" group.

When only the errors of patients with a lesion limited to the parietal lobe were analyzed, a significant interaction of the side of the lesion factor with the spatial relation factor was revealed [$F(1/9) = 10.93; p < 0.009$]. As expected, LH patients made more categorical errors than RH patients did, and RH patients made more coordinate errors than the LH patients did. The same pattern of results was also apparent for the parietal and temporal lesion group, although it did not achieve significance. The parietal and frontal lesion group's results also showed the same pattern of results of the previous three groups, which, in this case, was significant [$F(1/10) = 9.40; p < 0.01$].

Similarity Test

As shown in Figure 4B, which represents the number of categorical choices minus the number of coordinate choices, LH patients in each group tended to make more categorical choices than RH patients.

Patients with either left-sided or right-sided lesions limited to the parietal lobe significantly differed in number of categorical choices [$F(1/8) = 5.28; p < 0.05$]. This was also true for the groups of patients with parietal and temporal lesions [$F(1/17) = 5.81; p < 0.03$]. However, the groups of patients with parietal and frontal lesions did not differ significantly.

Aphasia Scores

Performance in the two aphasia tests (Boston Naming and Token tests) was converted to percentage of correct responses. Subsequently, two multiple-correlation analyses were performed, with the identity scores (categorical errors minus coordinate errors) or similarity test (number of categorical choices) as the criterion and performance in the two aphasia tests (percentage of correct responses) as the predictors. Neither of these analyses revealed significant correlations. More specifically, for the identity test $r = 0.19$ [$F(2, 5) = 0.621$; n.s.]; for the similarity test $r = 0.49$ [$F(2, 5) = 2.41$; n.s.].

Spatial Categories

Scores in the similarity test, and in the identity test for the categorical items only (i.e., those items where a categorical change occurred; N = 10), were grouped by type of categorical relation. Statistical analyses were then performed in order to assess whether all or some of these spatial categories accounted for the difference between the two groups of patients and the control group.

Identity Test

Four spatial categories were manipulated in this test: laterality [number of items (N) = 2], verticality ($N = 2$), confrontation ($N = 5$), and inclusion ($N = 1$). Laterality describes a relation between two objects of the type "left of/right of" and also, in the case of a single animal (who possesses an intrinsic left and right side), a change of what side of the animal is in view in the drawing. Verticality describes a relation between objects of the type "above/below." Confrontation describes any spatial relation between two animals on the horizontal plane. Types of relation such as "in front of/behind," "towards/away," but also "giving the left/right side," would be described by this category. Inclusion describes a relation between objects of the type "inside/outside."

Table 1. Site of Lesion[a]

	A			
	Number of Subjects	*Age*	*Sex (F/M)*	*Days of Recovery Mean (SD)*
Left lesion	30	63	14/16	230 (287)
Right lesion	30	63	10/20	162 (163)
No lesion	15	60	5/10	

	B	
	Left Lesion	*Right Lesion*
P	6	5
P+T	9	10
P+F	7	5
P+T+F	2	4
Other	6	6

[a](A) Number of subjects, mean age, proportion of females (F) over males (M), and average number of days and standard deviation of recovery time in each subgroup divided by side of the lesion (left, right, no). (B) Number of subjects in each subgroup divided by region of the lesion (P, parietal; P+T, parietal and temporal; P+F, parietal and frontal; P+T+F, parietal, temporal and frontal; other, other combinations of a lesion in the parietal lobe and other regions, (e.g., parietal and occipital) and by side of the lesion (left, right, no).

To examine the effect of different categories, separate ANOVAs were performed for the number of errors in one category with lesion as the between-subjects factor. The analysis for the categories of verticality and laterality failed to reveal any significant difference between groups of subjects. However, the analysis of the category of confrontation did show a significant effect of lesion [$F(2/71) = 14.22; p < 0.0001$] whereas that for the inclusion category approached significance [$F(2/71) = 2.805$; $p < 0.067$]. Post hoc Scheffe's tests showed that, in the case of the confrontation category, LH patients differed significantly from either the RH patients ($p < 0.0007$) or the normal subjects ($p < 0.0001$). For the inclusion category, the Scheffe's test, showed that LH patients differed more from the normal subjects ($p < 0.071$) than from the RH patients (n.s.).

For all of the four categories, the mean number of errors of the LH patients was always greater than that of the RH patients. Thus showing that a similar trend toward more "categorical" impairment for the LH group held for all of the category types, although the effect was clearer in the confrontation and inclusion conditions.

Similarity Test

Five spatial categories were included in this test. These were the four spatial categories already described in the previous section (laterality, $N = 9$; verticality, $N = 7$; confrontation, $N = 12$; inclusion, $N = 5$) with the addition of the category of "contact" ($N = 7$), describing a relation of the type "attached to/separate."

Separate ANOVAs were performed for each of the five spatial categories. According to these analyses, the between-subjects factor of lesion significantly affected the number of errors for transformations in the spatial categories of confrontation, laterality, and verticality but not for those of inclusion and contact. Post hoc Scheffe's tests showed that the LH patients differed from the RH patients by choosing the categorical transformation as more similar to the sample more often than the coordinate transformation in the confrontation ($p < 0.003$), laterality ($p < 0.015$), and verticality ($p < 0.033$) conditions. In all of these three conditions the group of normal subjects chose the categorical transformation at an intermediate level between the two groups of patients without differing significantly from them.

Number of Objects

In both the identity and similarity tests a few items involved manipulations of categorical and coordinate relations in one single object. An example of such transformations on a single object would be the following: consider a dog sitting and seen in profile (its left side in view) as the sample drawing; a categorical transformation would consist of a 180° rotation of its image (the dog is in the same position but shows its right side now); a coordinate transformation would consist in a

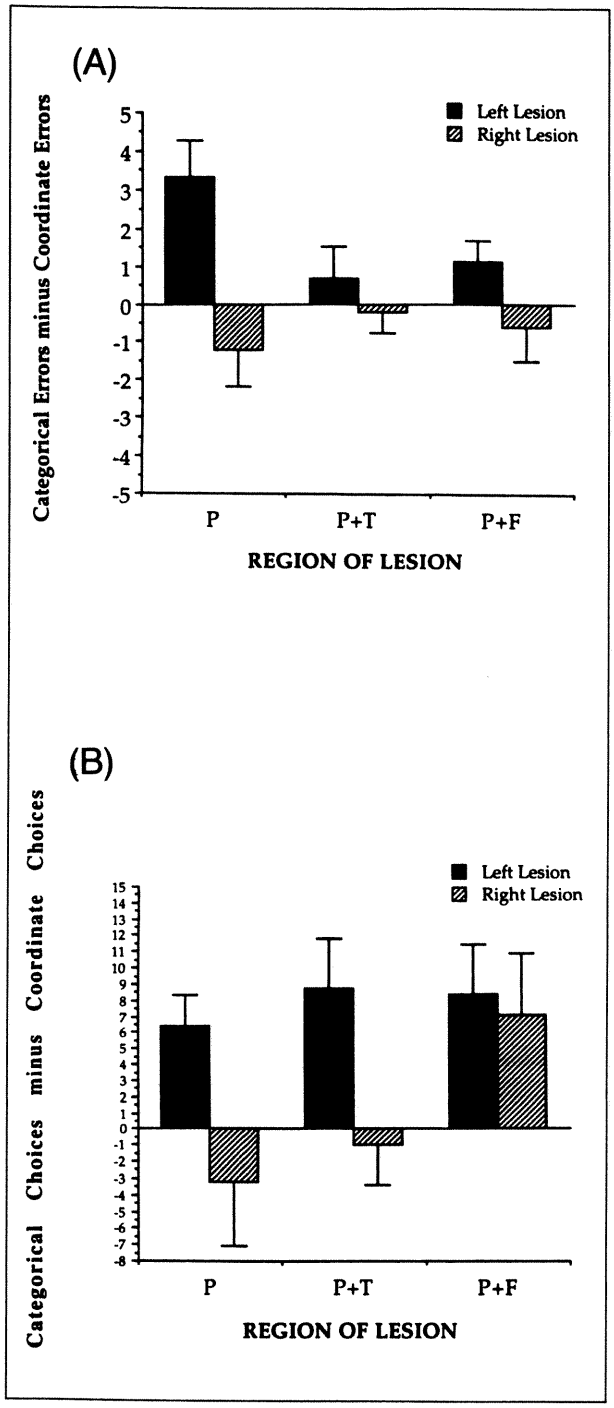

Figure 4. (**A**) Identity test. Mean and standard error of number of errors for items with transformations in categorical spatial relations *minus* the number of errors for items with transformations in coordinate spatial relations for each group of patients divided by region of lesion (P, parietal; P+T, parietal and temporal; P+F, parietal and frontal) and side of lesion (left, right). (**B**) Similarity test. Mean and standard error of number of choices for match drawings with transformations in categorical spatial relations *minus* the number of choices for match drawings with transformations in coordinate spatial relations for each group of patients divided by region of lesion (P, parietal; P+T, parietal and temporal; P+F, parietal and frontal) and side of lesion (left, right).

drawing where the dog is still seen in the same profile view of the sample but it is now, for instance, jumping instead of sitting.

Identity Test

Four items (two categorical and two coordinate) of the 20 comprising the whole test consisted of a single object. ANOVAs with lesion as the between-subjects factor, spatial relation and number of objects (one/two) as the within-subjects factors, and percentage of errors as the dependent variable was performed separately for two-objects items and one-object items.

When the two-objects items were analyzed separately, a significant effect of the interaction between lesion and relation emerged [$F(2/72) = 9.8$; $p < 0.0002$]. As described earlier for the whole test, LH patients made more categorical percent errors (mean = 35.78; SE = 4.79) than RH patients (mean = 18.75; SE = 3.32) and controls (mean = 10.83; SE = 2.40), whereas RH patients made more coordinate percent errors (mean = 32.08; SE = 3.68) than LH patients (mean = 19.39; SE = 3.01) and controls (mean = 11.67; SE = 3.10).

In the analysis of only one-object items, the main effect of lesion [$F(2/71) = 2.95$; $p < 0.05$] was significant. LH patients made more errors than the control subjects ($p < 0.07$). There was no significant interaction of this factor with the spatial relation factor.

Similarity Test

Seven items of the 40 comprising the whole test consisted of a single object. Performances in these items only and two-objects items were analyzed separately. The analysis of two-objects items showed the expected effect of lesion [$F(2/69) = 5.05$; $p < 0.009$]. As seen for performance in the whole test, LH patients made significantly more percent categorical choices (mean = 57.56; SE = 1.85; $p < 0.006$) than the RH patients (mean = 48.48; SE = 1.79), whereas the normal subjects' group score (mean = 50.30; SE = 3.25) fell between the two patients' group scores and did not differ significantly from them.

The analysis of the one-object condition also showed a significant effect of lesion [$F(2/69) = 5.81$; $p < 0.05$]. LH patients made more percent categorical choices (mean = 73.55; SE = 3.63) than RH patients (mean = 62.56; SE = 4.33). Normal subjects made more categorical choices (mean = 77.14; SE = 4.79) than either group of patients.

DISCUSSION

Background

If we examine the neuropsychological literature on spatial skills, it seems that of the two types of spatial per-

ception, the coordinate type has been more extensively investigated. There is considerable evidence that the right hemisphere is superior in tasks that require perception or memory of precise position, distance, and orientation of stimuli. Right hemisphere damage is consistently associated with impairment in spatial tasks such as navigation (Hécaen & Albert, 1978; De Renzi, 1982), position discrimination (Shankweiler, 1961; Warrington & Rabin, 1970; Hannay, Varney, & Benton, 1976; Fisk & Goodale, 1988; Warrington & James, 1988), orientation of lines and other geometric figures (McFie, Piercy, & Zangwill, 1950; Warrington & Rabin, 1970; De Renzi, Faglioni, & Scotti, 1971; Taylor & Warrington, 1973; Benton, Hannay, & Varney, 1975; Bisiach, Nichelli, & Spinnler, 1976; Benton, Varney, & Hamsher, 1978a; Layman & Greene, 1988), and fine discrimination of shapes or objects (Semmes, 1965; De Renzi & Scotti, 1969; Milner & Taylor, 1972).

Experimental studies with normal subjects have shown the superiority of the right hemisphere over the left in visual tasks of position discrimination (Kimura, 1969; McKeever & Huling, 1970; Levy & Reid, 1978; Allard & Bryden, 1979; Horwitz, Grady, Haxby, Schapiro, Rapoport, Ungerleider, & Mishkin, 1992), orientation of lines[1] (Fontenot & Benton, 1972; Atkinson & Egeth, 1973; Kimura & Durnford, 1974), fine discriminations of shapes or configurations (White & White, 1975; Sasanuma, Itoh, Mori, & Kobayashi, 1977; Axelrod, Leiber, & Noonan, 1978; Poizner & Lane, 1979), or of size (Hatta, 1977). Studies of the tactile modality showed, consistently to the visual studies, that line slants are perceived better with the left hand by normal subjects (Benton, Levin, & Varney, 1973; Witelson, 1974, 1976; Benton, Varney, & Hamsher, 1978b; Dodds, 1978; Oscar-Berman, Rehbein, Porfert, & Goodglass, 1978) and that the same is true for shape discriminations (Rudel, Denckla, & Spalten, 1974; Rudel, Denckla, & Hirsch, 1977; Witelson, 1974, 1976; Smith, Chu, & Edmonston, 1977).

Studies with commissurotomized patients also support the view that the right hemisphere is specialized for coordinate spatial function. In these patients, the left hand is superior in drawing, copying, and block constructions (Bogen & Gazzaniga, 1965; Gazzaniga, Bogen, & Sperry, 1965), or in feeling forms to be matched to pictures or objects inspected visually (Levy-Agresti & Sperry, 1968; Nebes, 1971, 1972, 1973; Zaidel & Sperry, 1973; Franco & Sperry, 1977). Gazzaniga and LeDoux's view (LeDoux, Wilson, & Gazzaniga, 1977; Gazzaniga & LeDoux, 1978) that the right hemisphere has advantage, particularly in tasks requiring manual praxis, is consistent with the idea that coordinate spatial perception is particularly important in guiding manipulations of objects and that it is a right hemisphere's specialization.

Spatial long-term memory, as tested with performance with mazes (i.e., "manual navigation" tasks), also seems to depend more on right hemisphere function than left (Corkin, 1965; Milner, 1965, 1971; Newcombe & Russel, 1969; Ratcliff & Newcombe, 1973; De Renzi, Faglioni, & Scotti, 1971; Hécaen, Tzortzis, & Rondot, 1980). Geographic knowledge (e.g., pointing or tracing on a map the location of cities or states) is also more frequently impaired after right than left hemisphere damage (Hécaen & Angelergues, 1963; Benton, Levin, & Van Allen, 1974). Topographical disorientation; a disorder in navigating in the physical environment, has often been associated with right hemisphere disease (Paterson & Zangwill, 1944; De Renzi, 1977; McCarthy & Warrington, 1990).

The examination of pictorial or constructional productions of patients would seem a particularly ideal method to reveal differential distortions in spatial relations. However, the results of studies involving constructions and drawings are usually controversial, since constructional tasks also tax praxic functions. Of many studies (McFie & Zangwill, 1960; Arrigoni & De Renzi, 1964; Warrington, James, & Kinsbourne, 1966; McGlone & Kertesz, 1973; Arena & Gainotti, 1978), none was conducted in the light of a specific theory of lateralization of separate spatial subsystems and they may have therefore overlooked important qualitative differences in the performance of patients.

All of the above observations have contributed to the growth of the widely accepted view that the right hemisphere is the "visuospatial" hemisphere. The left hemisphere's specialization for some type of spatial functions is not prominent in the literature, perhaps because categorical spatial representations have rarely been investigated. Nevertheless, some spatial disorders that may be interpreted as impairments of categorical perception have been described. Interestingly, they seem to be common after left hemisphere lesions.

Many authors agree that left/right confusion stands out in left hemisphere pathology as a peculiar spatial disorder (e.g., Gerstmann, 1924, cited in Benton, 1966; McFie & Zangwill, 1960; Semmes, Weinstein, Ghent, & Teuber, 1963; Luria, 1966; Poeck & Orgass, 1967; Saguet, Benton, & Hécaen, 1971; Benton, 1985).

Luria (1966) observed that verbal structures expressing spatial relationships (like the adverbial clauses "to the right of") were particularly difficult to understand for patients with left parietotemporal–occipital lesions. Patients with left posterior lesions also showed more markedly than patients with right-sided lesions signs of mistaking mirror-image relationships (e.g., in letters, patterns, and clock reading), reversals of east/west relationships in map drawing, and confusions between the left and right hand, i.e., "finger agnosia" (see Luria, 1966, p. 176; and also Kinsbourne & Warrington, 1962).

The ability to find or reconstruct a figure *inside* or embedded in another figure also seems to depend more on the left hemisphere than on the right (as in the Gottschaldt Test; Teuber & Weinstein, 1956; Russo &

Vignolo, 1967; Zaidel, 1978; Corkin, 1979; Kaplan, 1983; Stiles & Nass, 1991). This effect, however, may also depend on different biases of the two hemispheres in processing spatial frequency information (Sergent, 1982; Christman, 1989; Ivry, Robertson, & Lebby, 1992).

Kosslyn (1987) offered a rationale for a left hemisphere specialization of categorical spatial relations. He and his colleagues have pointed out that language, for which left hemisphere function is critical, hinges on category formation and suggested that (Kosslyn et al., 1989, p. 24; see also Liberman, 1970; Studdert-Kennedy & Shankweiler, 1970; Studdert-Kennedy, Liberman, Harris, & Cooper, 1970) the left cerebral hemisphere may develop other types of categorical processing, including those used in spatial perception.

Kosslyn has also offered some empirical support for this view by the demonstration that normal subjects respond faster when categorical judgments of spatial relations are made to stimuli presented tachistoscopically in the right visual field than in the left visual field, whereas when coordinate judgments are made tachistoscopic presentations in the left visual field lead to faster performance (Kosslyn, 1987; Kosslyn et al., 1989).

Hellige and Michimata (1989) have replicated Kosslyn and colleagues' results with normal subjects. Servos and Peters (1990) found a strong right visual field advantage for categorical perceptual judgments. Sergent (1991a), however, failed to replicate the findings of the above mentioned studies. Sergent (1991a, 1991b) also pursued further the issue of testing Kosslyn's two-process theory by investigating visual field differences with three commissurotomized patients and concluded that both hemispheres can process both types of spatial relations. However, as Sergent pointed out (1991b), negative results in split-brain patients are ambiguous. Equivalencies between disconnected hemispheres might be of little relevance for the understanding of normal hemispheric specialization.

Mehta, Newcombe, and Damasio (1987) and Mehta and Newcombe (1991) reported impairments in shape matching and rotation in left hemisphere cases and they claimed that these deficits were due to the loss in these patients of categorical spatial descriptions of the parts of multipart objects (which are at the basis of tasks such as mental rotation; see Farah, 1984, 1989; Kosslyn, 1987; Kosslyn & Koenig, 1992).

Present Findings

The study presented here offers some findings within the clinical domain of investigation that bring additional converging evidence with the aforementioned studies. The hypotheses of a "loss" of categorical and coordinate spatial function that can be derived from the theory were confirmed in this study by the qualitatively different patterns of perceptual impairment and shifts of perceptual sense of similarity shown by two comparable groups of stroke patients.

The Kind of Impairments in Spatial Perception Depended on Which Side of the Brain Was Affected by the Lesion

The two groups of patients showed clear differential impairments in recognizing the identity of stimuli differing along certain spatial relations and a differential "shift" in the perception of similarity also consistent with their deficit in failing to distinguish transformations in particular spatial relations.

In the identity test, LH patients mistakenly recognized as identical to the original sample the categorical transformations, whereas RH patients mistakenly recognized as identical to the original sample the coordinate spatial transformations. The two groups of patients did not differ significantly in total number of errors; rather they tended to commit different types of errors as predicted from Kosslyn's theory. Moreover, LH and RH patients were significantly impaired in, respectively, categorical and coordinate spatial judgments relative to the normal population. Normal subjects' coordinate errors were not significantly more frequent than their categorical errors, whereas RH patients showed more coordinate errors than categorical errors and the LH patients showed the converse pattern of errors.

In the similarity test, LH patients more often judged as similar the drawing transformed "categorically" than RH patients and control subjects did, whereas RH patients judged as more similar the drawing transformed along categorical spatial dimensions less frequently than the control subjects. The control subjects' preference for a transformation in one spatial relation or the other appeared to be more variable than that of the patient groups and to be equally distant from the average performance of these latter groups.

The relationship of the two groups of patients' performance to that of the control subjects was therefore identical in the two tests, despite the fact that in the identity test the control subjects tended to make no errors, whereas in the similarity test their performance was skewed toward one type of response (the categorical changes). It is likely that this preference of all subjects for the categorical changes, instead of revealing some built-in perceptual preference, was most likely the result of differences in difficulty between the items in the two tasks. This difference might have been reduced by adjusting the parameters along which the items were constructed.

Contrary to expectations, the identity test did appear as the most sensitive test of the two in revealing distortions in the perception of spatial relations after unilateral lesions. This was demonstrated by the larger differences

of percent scores between groups and a stronger effect size for the identity test than the similarity test.

One can conclude from the findings described above that left- and right-sided lesions resulted in qualitatively different impairments in the capacity to encode the stimuli differing in categorical or coordinate spatial relations and/or in the capacity to sustain an encoding of these stimuli in the short-term memory.

Inferring Two Separate Representational Systems for Spatial Relations

The complementary pattern of deficits in the two spatial perception tasks suggests that two separate systems, one in each hemisphere, underlie spatial perception. Therefore, the deficits in spatial function not only demonstrate a differential specialization of the cerebral hemispheres, but also provide evidence for the existence of distinct processing systems. The results are contrary to the view that a single subsystem could compute all spatial relations. If a single subsytem were responsible for the perception of both types of spatial relations, the two different types of lesion could have not been dissociated with impairments of each spatial relation in a complementary manner. The observed double dissociation (Teuber, 1955; Weiskrantz, 1968; Kinsbourne, 1971; Shallice, 1988) leaves no doubt that two subsystems must underlie the processing, since, logically, no other possible arrangement in cerebral function would explain why each lesion group is selectively impaired (and equally in severity) in only one type of spatial relation.

However, whereas the finding that the impairments in the two conditions are *reversed* for the two groups of patients points to more than one submechanism, it does not support directly the idea that these two submechanisms are both of a "spatial" nature. The findings could be alternatively interpreted as showing that the right hemisphere is more specialized for visuospatial function in general than the left. The greater impairment in coordinate tasks versus categorical tasks shown by the right hemisphere patients may just reflect the fact that the coordinate task is "harder" than the categorical. Additionally, since categorical spatial relations can be easily labeled verbally (by prepositions and locatives), a verbal strategy (i.e., mentally naming the spatial relations and memorizing the verbal description) may be more effective than a purely spatial strategy in solving certain easy spatial problems. Therefore, given that categorical spatial function would be more affected than the coordinate one by language deficits, the LH patients' impairment in the categorical tasks might simply reflect their loss of a language strategy (Goodglass, Denes, & Calderon, 1974) in solving one type of spatial task.

However, the above-described interpretation can be disproved on empirical grounds: (1) the symmetrical reversal of deficits, or cross-over interaction, rules out the possibility that a difference in difficulty of the two conditions can alone account for the pattern of findings; and (2) several patients who in the aphasia test, or in casual conversation, showed no signs of language impairments were nevertheless impaired in recognizing the occurrence of categorical transformations in the drawings. Additionally, some severely aphasic patients were not impaired in any of the categorical spatial tasks. Moreover, the degree of language impairment, as measured by standard aphasia tests, did not correlate with performance in the spatial tasks, as it would have been expected if a deficit in such strategy was really underlying the left hemisphere cases' performance.

It is possible that further research would show that patients with impairment in categorical spatial perception also show a specific isolated impairment in naming categorical spatial relations. This finding would suggest (as already hinted by Luria, 1966) that such difficulties with certain logical-grammatical structures concerning space would not be the cause but the result of a deficit in spatial functions.

Finally, the possibilty that the present findings may result from different biases in perceiving different spatial frequencies (Sergent, 1982; Christman, 1989; Ivry et al., 1992; Kosslyn, Chabris, Marsolek, & Koenig, 1992) can also be discarded. The categorical transformations did not involve, in fact, any change in spatial frequency and about half of the items with coordinate transformations involved a change into a relatively higher spatial frequency (i.e., the space between the two objects was compressed) or no appreciable change in such variable (see, for instance, Fig. 1C). Nevertheless, as suggested by both Kosslyn et al. (1992) and Ivry et al. (1992), hemispheric differences in early processing of spatial frequencies may lie at the basis of the formation of other higher-order spatial representations.

The Relevance of the Parietal Lobe

Although no definite conclusions about the relationship between neuroanatomical areas and deficits in spatial relations can be derived from the results presented in this study, the greater losses in spatial function occurred after lesions that were, according to the neuroradiologists' reports of CT and MRI scans, limited to the parietal lobe only (see Fig. 4). When lesions tended to include other cortical lobes (the temporal and, especially, the frontal), impairments in spatial function were less pronounced. This finding might suggest that in these patients, the focus of the lesion might have been located more anteriorly than in the "parietal only" cases and, therefore, not affecting as much a hypothetically primary functional area for spatial relations contained within the parietal lobe and posteriorly. That a cortical "center" for processing spatial relations would be located in the parietal areas would not be surprising, since the relevance of the parietal areas for visuospatial function is already

well known (Luria, 1966; De Renzi, 1982; Mishkin, Ungerleider, & Macko, 1983).

Spatial Categories

Some categories seemed to be perceived and/or remembered with more difficulty by LH patients compared to RH patients and normal subjects. In particular, the spatial category of confrontation (i.e., all those relations between objects possessing "intrinsic" sides, like animals or certain manmade objects) was, consistently, in both tasks, the most affected by left-sided lesions. All categories, nevertheless, tended to be more affected by left-sided lesions than right-sided lesions. Since the perception of the visual world according to spatial relations is dynamic and develops slowly with learning and exposure to specific spatial problems, it could be hypothesized that if cerebral lateralization also develops slowly, then those categorical relations that are learned later in development will depend more on a lateralized system than the earlier ones (see, however, Kinsbourne & Hiscock, 1977, for a contrasting view).

Alternatively, more difficult spatial relations may require the greater power of one side of an asymmetrically organized cognitive system. The left/right distinction is usually learned the latest among spatial relations (at about 7–8 years age; e.g., Terman, 1916; Piaget, 1928; Ames & Learned, 1948; Inhelder & Piaget, 1956; Benton, 1959; Elkind, 1961; Belmont & Birch, 1963; Swartz & Hall, 1972; Clark, 1973; Miller & Johnson-Laird, 1976). It is possible that the relations between the intrinsic sides of objects, or object-centered categorical relations, would be the most difficult and the most sensitive to left-sided damage.

Spatial Relations Between Two Objects or Within One Object

The effect of unilateral cerebral damage on each type of spatial relation seemed to hold, as shown by performance in the similarity test, for both the between-objects (as expected) and the within-object relations. The lateralization of categorical/coordinate representation may not be limited to the special case of relations between objects but apply as well to the spatial analysis of single shapes.

METHODS AND PROCEDURES

Subjects

Thirty patients with left-sided cerebral strokes and 30 patients with right-sided cerebral strokes were recruited for the study from inpatients at the following rehabilitation institutions: Clinica S. Lucia in Rome (Italy), Rehabilitation Institute of Michigan, Detroit (Michigan), and the V.A. Hospital and the University Hospital in Ann Arbor (Michigan). Patients with neurological diseases other than stroke, or with dementia, substance abuse, and psychiatric disorders were excluded. The location of the lesions was determined by neuroradiologists's reports of CT or MRI scans. Fifteen control subjects were included in the study. One third of the control subjects were nonhospitalized individuals without any history of neurological disorders; they lived in the city of Rome (Italy). The remaining subjects were examined in Ann Arbor, Michigan; half of them were hospitalized individuals with diabetic, pulmonary, or cancer problems at the V.A. Hospital in Ann Arbor (Michigan). None of the control subjects had any history of neurological disorders.

The three groups did not differ in age [$F2, 72) = 0.30$, n.s.] or education [$F(2, 72) = 0.30$, n.s.]. The two groups of brain-damaged patients did not differ in time since the onset of symptoms to day of testing [$t(58) = 1.14$, n.s.].

Test Material

Two-dimensional shapes, in color or black-and-white, were used. They depicted mainly animals but also common objects and geometric figures. They ranged in size of the longest axis from 0.5 to 5.5 cm and were presented on a white background provided by 7.5 × 12.6 cm cards.

The following basic categorical spatial relations were selected: laterality (i.e., left of/right of), verticality (above/below), confrontation (in front of/behind; or toward/away), inclusion (inside/outside), and contact (on/off; or attached to/detached). The following coordinate variations were presented: distance on the horizontal axis, distance on the vertical axis, distance on both axes, distance relative to a frame, position of body parts, orientation (in angle), and object size.

Procedures

Identity Test

This test included 20 pairs of items, each consisting of a sample figure (presented first, by itself) and a match figure (i.e., a variant depiction of the same object(s) differing in either a categorical or coordinate spatial relations), presented later with the sample figure. The match figure for half of the pairs differed in categorical relations, whereas the other half differed in coordinate relations.

Subjects sat in front of a table; the experimenter faced them from the other side. The experimenter showed the sample card flat on the table in full view of the patient. The position of all the item cards was shifted to the "good" side (the right) in those patients with right hemispheric lesions who showed symptoms of neglect in clinical tests (i.e., cancellation tasks). The subjects were asked by the experimenter to examine carefully the sample figure and try to remember it, because shortly afterward the subject would be asked to identify it. The study

time for the sample drawing was approximately 5 sec (the experimenter counted mentally from one to five). Then the sample card was removed; after an interval of approximately another 5 sec it was shown again together with the variant match card. The subject was then asked to point manually to the card that was identical to the previously shown sample card. Correct responses and errors (i.e., pointing to the drawing with a change in one of the two spatial relations) were recorded by the experimenter after each trial. The 20 pairs of items were presented to the subjects in a pseudorandom order. The position of the sample and match cards relative to each other (i.e., left/right or top/bottom) when displayed together on the table was also varied randomly from trial to trial.

Preliminary Figure Recognition Test

Before the identity test was performed, a short test consisting of 5 items was administered in order to familiarize the subject with the procedures and assess whether the basic perceptual capacity to recognize differences between figure shapes was spared. Procedures were identical to the ones described above for the identity test. In this recognition test, the sample always consisted of a color drawing of an animal (e.g., a dog) and the match consisted of the drawing of another exemplar of the same species (e.g., another dog, different in color, morphology, or position). Subjects who were unable to point to the first drawing on all of the five trials were excluded from further testing.

Another purpose of this task was to familiarize the appropriate subjects with the testing procedures to be used in the tests to follow. This task also allowed the experimenter to explain to those left hemisphere cases with aphasic symptoms (particularly in speech comprehension) how to perform the task. For these patients, the experimenter first showed the sample and then, when sample and match were shown together, he pointed to the correct drawing. Subsequently, the experimenter would guide the hand of the patient to point to the correct card. After that, the experimenter, using gestures, would encourage the patient to point independently.

Similarity Test

This test consisted of 40 items and was always administered after the identity test. It consisted of an original sample figure, and two variant figures presented in the matching portion of each trial: one in which a change in categorical spatial relations of the sample drawing was introduced without changing coordinate spatial relations, and another version in which a change in coordinate spatial relation was introduced without changing categorical relations. After presenting the two matches, the experimenter asked subjects to point to the card that showed a drawing that looked "more similar" to the previous one.

The aphasic patients who had difficulty understanding the instructions were, nevertheless, capable of performing the task simply by continuing, despite some perplexity, to respond in the same manner (i.e., looking for the "same" picture) that they did in the previous identity test. The subjects' choices ("categorical" or "coordinate") were recorded by the experimenter after each trial.

Aphasia Tests

More than half (N = 20) of the LH patients received additional testing with the Token Test (De Renzi & Vignolo, 1962) and/or the Boston Naming Test (Goodglass & Kaplan, 1983) in order to assess their degree of language impairment, so as to analyze its correlation with performance in the categorical spatial task.

Acknowledgments

The author is particularly thankful to the following people for their interesting and useful comments on several versions of the manuscript: Rudolf Arnheim, Gus Buchtel, Charlie Butter, Stephen Kosslyn, Sarah Newman, Michael Peters, and Elliot Valenstein. Also special thanks go to Doctors Pizzamiglio, Amadio, and Berardi at the Clinica S. Lucia in Rome, Doctor Cole at the University Hospital in Ann Arbor, and Doctor Lamb at the Rehabilitation Institute of Michigan in Detroit.

Reprint requests should be sent to Bruno Laeng, Department of Psychology, McKinnon Building, University of Guelph, Guelph, Ontario, CANADA N1G 2W1.

Note

1. When lines are oriented in canonical positions (of which verbal labels are easily available in the lexicon, like up, left, diagonal, etc.) the left hemisphere seems to be superior to the right in recognizing such positions (White, 1971; Umiltá, Rizzolatti, Marzi, Zamboni, Franzini, Camarda, & Berlucchi, 1974). These findings suggest that either the left hemisphere is using its well-known verbal abilities as a strategy to solve the task or that the left hemisphere has developed specific categorical spatial representations of "marked" (canonical) spatial positions, that are also at the basis of the verbal communication on space (see also De Renzi, 1982, p. 148; Shepard & Hurwitz, 1985; Kosslyn, 1987; Kosslyn, Koenig, Barrett, Cave, Tang, & Gabrieli, 1989).

REFERENCES

Allard, F., & Bryden, M. P. (1979). The effect of concurrent activity on hemispheric asymmetries. *Cortex, 15,* 5–17.

Ames, L. B., & Learned, J. (1948). The development of verbalized space in the young child. *Journal of Genetic Psychology, 68,* 97–125.

Arena, R., & Gainotti, G. (1978). Constructional apraxia and

visuoperceptive disabilities in relation to laterality of cerebral lesions. *Cortex, 14,* 463–473.
Arrigoni, G., & De Renzi, E. (1964). Constructional apraxia and hemispheric locus of lesion. *Cortex, 1,* 170–197.
Atkinson, J., & Egeth, H. (1973). Right hemisphere superiority in visual orientation matching. *Canadian Journal of Psychology, 27,* 152–158.
Axelrod, S., Leiber, L., & Noonan, M. (1978). Classification of random forms and distortions presented to the left or right visual field. *Perception and Motor Skills, 47,* 615–621.
Belmont, L., & Birch, H. G. (1963). Lateral dominance and right-left awareness in normal children. *Child Development, 34,* 257–270.
Benton, A. (1959). *Right-left discrimination and finger localization.* Hoeber-Harper.
Benton, A. (1966). *Problemi di neuropsicologia.* Giunti Barbera.
Benton, A. (1985). Body schema disturbances: Finger agnosia and right-left disorientation. In K. M. Heilman & E. Valenstein, (Eds.), *Clinical neuropsychology,* 2nd ed. Oxford: Oxford University Press.
Benton, A. L., Hannay, H. J., & Varney, N. (1975). Visual perception of line direction in patients with unilateral brain disease. *Neurology, 25,* 907–910.
Benton, A. L., Levin, H. S., & Van Allen, M. W. (1974). Geographic orientation in patients with unilateral cerebral disease. *Neuropsychologia, 12,* 183–191.
Benton, A. L., Levin, H. S., & Varney, N. (1973). Tactile perception of direction in normal subjects. *Neurology, 23,* 1248–1250.
Benton, A. L., & Van Allen, M. W. (1968). Impairment in facial recognition in patients with cerebral disease. *Cortex, 4,* 344–358.
Benton, A. L., Varney, N., & Hamsher, K. de S. (1978a). Visuospatial judgment: A clinical test. *Archives of Neurology (Chicago), 35,* 364–367.
Benton, A. L., Varney, N., & Hamsher, K. de S. (1978b). Lateral differences in tactile directional perception. *Neuropsychologia, 16,* 109–114.
Bisiach, E., Nichelli, P., & Spinnler, H. (1976). Hemispheric functional asymmetry in visual discrimination between univariate stimuli: An analysis of sensitivity and response criterion. *Neuropsychologia, 14,* 335–342.
Bogen, J. E., & Gazzaniga, M. S. (1965). Cerebral commissurotomy in man: Minor hemisphere dominance for certain visuo-spatial functions. *Journal of Neurosurgery, 23,* 394–399.
Christman, S. (1989). Perceptual characteristics in visual laterality research. *Brain and Cognition, 11,* 238–257.
Clark, H. H. (1973). Space, time, semantics and the child. In T. E. Moore, (ed.), *Cognitive development and the acquisition of language.* New York: Academic Press.
Cohen, J. (1977). *Statistical power analysis for behavioral sciences.* New York: Academic Press.
Corkin, S. (1965). Tactually-guided maze learning in man: Effects of unilateral cortical excisions and bilateral hippocampal lesions. *Neuropsychologia, 3,* 339–351.
Corkin, S. (1979). Hidden-figures-test performance: Lasting effects of unilateral penetrating head injury and transient effects of bilateral cingulotomy. *Neuropsychologia, 17,* 585–605.
De Renzi, E. (1982). *Disorders of space exploration and cognition.* New York: John Wiley.
De Renzi, E., Faglioni, P., & Scotti, G. (1971). Judgment of spatial orientation in patients with focal brain damage. *Journal of Neurology, Neurosurgery, Psychiatry, 34,* 489–495.
De Renzi, E., & Scotti, G. (1969). The influence of spatial disorders in impairing tactual discrimination of space. *Cortex, 5,* 53–62.
De Renzi, E., & Vignolo, L. (1962). The Token Test: A sensitive test to detect receptive disturbances in aphasics. *Brain, 85,* 665–678.
Dodds, A. G. (1978). Hemispheric differences in tactuo-spatial processing. *Neuropsychologia, 16,* 247–250.
Elkind, D. (1961). Children's conception of right and left: Piaget replication study IV. *Journal of Genetic Psychology, 99,* 269–276.
Farah, M. J. (1984). The neurological basis of mental imagery: A componential analysis. *Cognition, 18,* 245–272.
Farah, M. J. (1989). The neuropsychology of mental imagery. In F. Boller & J. Grafman, (Eds.), *Handbook of neuropsychology* (Vol. 2). Amsterdam: Elsevier.
Fisk, J. D., & Goodale, M. A. (1988). The effects of unilateral brain damage on visually guided reaching: Hemispheric differences in the nature of the deficit. *Experimental Brain Research, 72,* 425–435.
Fontenot, D. J., & Benton, A. L. (1972). Perception of direction in the right and left visual fields. *Neuropsychologia, 10,* 447–452.
Franco, L., & Sperry, R. W. (1977). Hemisphere lateralization for cognitive processing of geometry. *Neuropsychologia, 15,* 107–114.
Gazzaniga, M. S., Bogen, J. E., & Sperry, R. E. (1965). Observations on visual perception after disconnexion of the cerebral hemispheres in man. *Brain, 88,* 221.
Gazzaniga, M. S., & LeDoux, J. E. (1978). *The integrated mind.* New York: Plenum Press.
Goodglass, H., Denes, F., & Calderon, M. (1974). The absence of covert verbal mediation in aphasia. *Cortex, 10,* 264–269.
Goodglass, H., & Kaplan, H. (1983). *The assessment of aphasia and related disorders.* Philadelphia: Lea & Fabiger.
Hannay, H. J., Varney, N., & Benton, A. L. (1976). Visual localization in patients with unilateral brain disease. *Journal of Neurology, Neurosurgery, Psychiatry, 39,* 307–313.
Hatta, T. (1977). Recognition of Japanese Kanji in the left and right visual fields. *Neuropsychologia, 15,* 685–688.
Hécaen, H., & Albert, M. L. (1978). *Human neuropsychology.* New York: John Wiley.
Hécaen, H., & Angelergues, R. (1963). *La cecité psychique.* Paris: Masson.
Hécaen, H., Tzortzis, C., & Rondot, P. (1980). Loss of topographical memory with learning deficits. *Cortex, 16,* 525–542.
Hellige, J. B., & Michimata, C. (1989). Categorization versus distance: Hemispheric differences for processing spatial information. *Memory and Cognition, 17,* 770–776.
Horwitz, B., Grady, C. L., Haxby, J. V., Schapiro, M. B., Rapoport, S. I., Ungerleider, L. G., & Mishkin, M. (1992). Functional associations among human posterior extrastriate brain regions during object and spatial vision. *Journal of Cognitive Neuroscience, 4,* 311–322.
Inhelder, B., & Piaget, J. (1956). *Child's conception of space.* New York: Norton.
Ivry, R., Robertson, L., & Lebby, P. (1992). Hemispheric processing of frequency information: A general model. (unpublished manuscript)
Kaplan, E. (1983). Process versus achievement revisited. In S. Wapner & B. Kaplan, (Eds.), *Toward a holistic developmental psychology.* Hillsdale, NJ: Erlbaum.
Kimura, D. (1969). Spatial localization in left and right visual fields. *Canadian Journal of Psychology, 23,* 445–448.
Kimura, D., & Durnford, M. (1974). Normal studies on the function of the right hemisphere in vision. In S. J. Dimond, & J. G. Beaumont, (Eds.), *Hemisphere function in the human brain.* Halsted Press.

Kinsbourne, M. (1971). Cognitive deficit: Experimental analysis. In J. L. McGaugh, (Ed.), *Psychobiology.* New York: Academic Press.
Kinsbourne, M., & Hiscock, M. (1977). Does cerebral dominance develop? In S. Segalowitz & F. A. Gruber, (Eds.), *Language development and neurological theory.* New York: Academic Press.
Kinsbourne, M., & Warrington, E. (1978). A study of finger agnosia. *Brain, 85,* 47–66.
Koenig, O., Reiss, L. P., & Kosslyn, S. M. (1990). The development of spatial relations representations: Evidence from studies of cerebral lateralization. *Journal of Experimental Child Psychology, 50,* 119–130.
Kosslyn, S. M. (1987). Seeing and imaging in the cerebral hemispheres: A computational approach. *Psychological Review, 94*(2), 148–175.
Kosslyn, S. M., Chabris, C. F., Marsolek, C. J., & Koenig, O. (1992). Categorical versus coordinate spatial relations: Computational analysis and computer simulation. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 562–577.
Kosslyn, S. M., & Koenig, O. (1992). *Wet mind. The new cognitive neuroscience.* The Free Press.
Kosslyn, S. M., Koenig, O., Barrett, A., Cave, C. B., Tang, J., & Gabrieli, J. D. E. (1989). Evidence for two types of spatial representations: Hemispheric specialization for categorical and coordinate relations. *Journal of Experimental Psychology: Human Perception and Performance, 15*(4), 723–735.
Landau, B., & Jackendoff, R. (1993). "What" and "where" in spatial language and spatial cognition. *Behavioral and Brain Sciences, 16,* 217–265.
Layman, S., & Greene, E. (1988). The effect of stroke on object recognition. *Brain and Cognition, 7,* 87–114.
LeDoux, J. E., Wilson, D. H., & Gazzaniga, M. S. (1977). Manipulo-spatial aspects of cerebral lateralization: Clues to the origin of lateralization. *Neuropsychologia, 15,* 743–750.
Levy, J., & Reid, M. (1978). Variations in cerebral organization as a function of handedness, hand posture in writing, and sex. *Journal of Experimental Psychology: General, 107,* 119–144.
Levy-Agresti, J., & Sperry, R. W. (1968). Differential perceptual capacities in major and minor hemispheres. *Proceedings of the National Academy of Science, U.S.A. 61,* 1151.
Liberman, A. M. (1970). Some characteristics of perception in the speech mode. In Hamburg, D. A., Pribram, K. H., & Stunkard, A. J., (Eds.), *Perception and Its Disorders.* Baltimore: Williams and Wilkins.
Luria, A. S. (1966). *Higher cortical functions in man.* New York: Basic Books.
McCarthy, R. A., & Warrington, E. K. (1990). *Cognitive neuropsychology. A clinical introduction.* San Diego: Academic Press.
McFie, J., Piercy, M. F., & Zangwill, O. L. (1950). Visual-spatial agnosia associated with lesions of the right cerebral hemisphere. *Brain, 73,* 167–190.
McFie, J., & Zangwill, O. L. (1960). Visual-constructive disabilities associated with lesions of the left cerebral hemisphere. *Brain, 83,* 243–260.
McGlone, J., & Kertesz, A. (1973). Sex differences in cerebral processing of visuospatial tasks. *Cortex, 9,* 313–320.
McKeever, W. F., & Huling, M. D. (1970). Lateral dominance in tachistoscopic word recognition at two levels of ability. *Quarterly Journal of Experimental Psychology, 22,* 600–604.
Mehta, Z., & Newcombe, F. (1991). A role for the left hemisphere in spatial processing. *Cortex, 27,* 153–167.
Mehta, Z., Newcombe, F., & Damasio, H. (1987). A left hemisphere contribution to visuospatial processing. *Cortex, 23,* 447–487.
Miller, G. A., & Johnson-Laird, P. N. (1976). *Language and perception.* Cambridge, MA: Harvard University Press.
Milner, B. (1965). Visually-guided maze learning in man: Effects of bilateral hippocampal, bilateral frontal, and unilateral cerebral lesions. *Neuropsychologia, 3,* 317–338.
Milner, B. (1971). Interhemispheric differences in the localization of psychological processes in man. *British Medical Bulletin, 27,* 272–277.
Milner, B., & Taylor, A. M. (1972). Right hemisphere superiority in tactile pattern recognition after cerebral commissurotomy: Evidence for nonverbal memory. *Neuropsychologia, 10,* 1–15.
Mishkin, M., Ungerleider, L. G., & Macko, K. A. (1983). Object vision and spatial vision: Two cortical pathways. *Trends in Neuroscience, 6,* 414–417.
Moscovitch, M. (1979). Information processing in the cerebral hemispheres. In M. S. Gazzaniga, (Ed.), *Handbook of behavioral neurobiology, Vol. 2: Neuropsychology.* New York: Plenum Press.
Nebes, R. D. (1971). Superiority of the minor hemisphere in commissurotomized man for the perception of part-whole relations. *Cortex, 7,* 333–349.
Nebes, R. D. (1972). Dominance of the minor hemisphere in commissurotomized man on a test of figural unification. *Brain, 95,* 633–638.
Nebes, R. D. (1973). Perception of spatial relationship by the right and left hemispheres in commissurotomized man. *Neuropsychologia, 11,* 285–290.
Newcombe, F., & Russell, W. R. (1969). Dissociated visual perceptual and spatial deficits in focal lesions of the right hemisphere. *Journal of Neurology, Neurosurgery, Psychiatry, 32,* 73–81.
Oscar-Berman, M., Rehbein, L., Porfert, A., & Goodglass, H. (1978). Dichaptic hand-order effects with verbal and nonverbal tactile stimulation. *Brain and Language, 6,* 323–333.
Paterson, A., & Zangwill, O. (1944). Disorders of visual space perception associated with lesions of the right cerebral hemisphere. *Brain, 67,* 331–358.
Piaget, J. (1928). *Judgment and reasoning in the child.* New York: Harcourt, Brace, & World.
Poeck, K., & Orgass, B. (1966). Gerstmann's syndrome and aphasia. *Cortex, 2,* 421–427.
Poizner, H., & Lane, H. (1979). Cerebral asymmetry in the perception of American Sign Language. *Brain and Language, 7,* 210–226.
Ratcliff, G., & Newcombe, F. (1973). Spatial orientation in man: Effects of left, right, and bilateral posterior cerebral lesions. *Journal of Neurology, Neurosurgery, Psychiatry, 36,* 448–454.
Rudel, R. G., Denckla, M. B., & Hirsch, S. (1977). The development of left-hand superiority for discriminating Braille configurations. *Neurology, 27,* 160–164.
Rudel, R. G., Denckla, M. B., & Spalten, E. (1974). The functional asymmetry of Braille letter learning in normal, sighted children. *Neurology, 24,* 733–738.
Russo, M., & Vignolo, L. A. (1967). Visual figure-ground discrimination in patients with unilateral cerebral disease. *Cortex, 3,* 113–127.
Sauguet, J., Benton, A. L., & Hécaen, H. (1971). Disturbances of body schema in relation to language impairment and hemispheric locus of lesion. *Journal of Neurology, Neurosurgery, Psychiatry, 34,* 496–501.
Sasanuma, S., Itoh, M., Mori, K., & Kobayashi, Yo. (1977). Tachistoscopic recognition of Kana and Kanji words. *Neuropsychologia, 15,* 547–553.

Semmes, J. (1965). A non-tactual factor in astereognosis. *Neuropsychologia, 3,* 295–315.
Semmes, J., Weinstein, S., Ghent, L., & Teuber, H. L. (1963). Correlates of impaired orientation in personal and extrapersonal space. *Brain, 86,* 747–772.
Sergent, J. (1982). The cerebral balance of power: Confrontation or cooperation. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 253–272.
Sergent, J. (1991a). Judgments of relative position and distance on representations of spatial relations. *Journal of Experimental Psychology: Human Perception and Performance, 91,* 762–780.
Sergent, J. (1991b). Processing of spatial relations within and between the disconnected cerebral hemispheres. *Brain, 114,* 1025–1043.
Servos, P., & Peters, M. (1990). A clear left hemisphere advantage for visuo-spatially based verbal categorization. *Neuropsychologia, 28,* 1251–1260.
Shallice, T. (1988). *From neuropsychology to mental structure.* Cambridge: Cambridge University Press.
Shankweiler, D. P. (1961). Performance of brain-damaged patients on two tests of sound localization. *Journal of Comparative Physiological Psychology, 54,* 375–381.
Shepard, R. N., & Hurwitz, S. (1985). Upward direction, mental rotation, and discrimination of left and right turns in maps. In S. Pinker, (Ed.), *Visual cognition* (pp. 161–193). Cambridge, MA: MIT Press.
Smith, M. O., Chu, J., & Edmonston, W. E. (1977). Cerebral lateralization of haptic perception: Interaction of responses to Braille and music reveals a functional basis. *Science, 197,* 689–690.
Stiles, J., & Nass, R. (1991). Spatial grouping activity in young children with congenital right and left hemisphere brain injury. *Brain and Cognition, 15,* 201–222.
Studdert-Kennedy, M., Liberman, A. M., Harris, K. S., & Cooper, F. S. (1970). Motor theory of speech perception: A reply to Lanes's critical review. *Psychological Review, 77,* 234–269.
Studdert-Kennedy, M., & Shankweiler, D. (1970). Hemispheric specialization for speech perception. *Journal of the Acoustical Society of America, 48,* 579–594.
Swartz, K., & Hall, A. E. (1972). Development of relational concept and word definition in children five through eleven. *Child Development, 43,* 239–244.
Taylor, A. M., & Warrington, E. K. (1973). Visual discrimination in patients with localized cerebral lesions. *Cortex, 9,* 82–93.
Terman, L. M. (1916). *The measurement of intelligence.* Boston: Houghton Mifflin.
Teuber, H. L. (1955). Physiological psychology. *Annual Review of Psychology, 9,* 267–296.
Teuber, H. L., & Weinstein, S. (1976). Ability to discover hidden figures after cerebral lesions. *Archives of Neurology and Psychiatry, 76,* 369–379.
Umiltá, C. A., Rizzolatti, G., Marzi, C. A., Zamboni, G., Franzini, C., Camarda, R., & Berlucchi, G. (1974). Hemispheric differences in the discrimination of line orientation. *Neuropsychologia, 12,* 165–174.
Warrington, E. K., & James, M. (1988). Visual apperceptive agnosia: A clinico-anatomical study of three cases. *Cortex, 3,* 317–326.
Warrington, E. K., James, M., & Kinsbourne, M. (1966). Drawing disability in relation to laterality of lesion. *Brain, 89,* 53–82.
Warrington, E. K., & Rabin, P. (1970). Perceptual matching in patients with cerebral lesions. *Neuropsychologia, 8,* 475–487.
Weiskrantz, L. (1968). Some traps and pontifications. In L. Weiskrantz, (Ed.), *Analysis of Behavioral Change.* New York: Harper & Row.
White, M. J. (1971). Visual hemifield differences in the perception of letters and contour orientation. *Canadian Journal of Psychology, 25,* 207–212.
White, M. J., & White, K. G. (1975). Parallel-serial processing and hemispheric function. *Neuropsychologia, 13,* 377–381.
Witelson, S. F. (1974). Hemispheric specialization for linguistic and non-linguistic tactual perception using a dichotomous stimulation technique. *Cortex, 10,* 3–17.
Witelson, S. F. (1976). Sex and the single hemisphere: Specialization of the right hemisphere for spatial processing. *Science, 193,* 425–427.
Zaidel, E. (1978). Concepts of cerebral dominance in the split brain. In P. A. Buser & A. Rougeul Busser, (Eds.), *Correlates of conscious experience.* Amsterdam: Elsevier.
Zaidel, E., & Sperry, R. W. (1973). Performance on Raven's colored progressive matrices tests by commissurotomy patients. *Cortex, 9,* 34.