



0028-3932(94)00126-X

CEREBRAL LATERALIZATION FOR THE PROCESSING OF SPATIAL COORDINATES AND CATEGORIES IN LEFT- AND RIGHT-HANDERS

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(Received 13 June 1994; accepted 23 October 1994)

Abstract—Subjects judged whether a tachistoscopically lateralized drawing was identical or different to a drawing seen immediately before in free vision. The drawings depicted natural objects (e.g. animals). On half of the trials the tachistoscopic drawing presented the same objects but either the categorical or the coordinate spatial relations (according to Kosslyn's definitions [23]) between the objects were transformed.

In the first experiment 38 right-handed subjects (half males and half females) were tested. Categorical judgements were faster when the match drawing appeared in the right visual field, whereas coordinate judgements were faster when the match drawing appeared in the left visual field.

In the second experiment 26 right-handed and 40 left-handed subjects participated. Almost all the subjects were female. Right-handed subjects replicated the findings of the subjects in the first experiment. However, the LHs did not show any difference in response times between spatial conditions and visual fields.

These findings support Kosslyn's hypothesis that the left and right hemispheres are specialized respectively for processing categorical and coordinate spatial relations. Moreover, they also suggest that this lateralization pattern is not typical of left-handers.

Key Words: neuropsychology; brain-localization; space perception; lateralization.

INTRODUCTION

There is evidence that space is represented by the human mind in terms of categorical and coordinate frames of reference. This evidence suggests that at least two separate regions of the human brain are differentially involved in the processing of each of these forms of spatial representation (e.g. Refs [25] and [31]).

The term “categorical”, as applied to spatial cognition, refers to our ability to perceive and express certain qualitative spatial aspects of the objects of our world. This qualitative knowledge is what typically informs our verbal exchanges about space. Relational terms between objects of experience are easily expressed in language with a range of grammatical terms that are specific to this purpose. Spatial prepositions, or locatives [35], express qualitative and discrete spatial relations between objects and lend themselves to quick, unambiguous descriptions (e.g. “in the car”, “to your left”, “on the bookshelf”, “behind you”, etc.). These locatives abstract the bare essentials of spatial relations by discarding unessential specifics. The value of spatial locatives in discourse is that a minimal common spatial frame of reference will suffice for meaningful communication. This form of describing spatial

relations is of great practical value where immediate action decisions have to be made, or where qualitative spatial relations of objects have to be communicated quickly.

The term “coordinate” refers to our ability to perceive and express quantitative aspects of the spatial relations of objects. This type of spatial representation seems necessary in order to control our movements in a physical medium, like in navigating in the environment or manipulating objects [26]. In verbal communications about these quantitative relations, there is no specific grammatical class in language. These aspects of space require descriptions that use an elaborate system of subdivisions, or metrics, of a coordinate framework. The degree of elaboration of such verbal descriptions has to depend on the degree of sophistication in commonly shared physical measurement (e.g. using the metric system).

Thus, we describe categorical and coordinate aspects of space in ways which are so different from each other as to suggest very different underlying mental operations. The effectiveness of statements like “three miles from here”, “ten inches long”, presuppose a culturally shared coordinate system and the ability to perform measurement procedures, and the veracity of a coordinate description of this type can only be ascertained by carrying out specific measuring operations. In contrast, the veracity of categorical descriptions (e.g. “it’s on the table”) of objects under view can be verified “directly” by a simple visual inspection.

Several studies have focused on the above distinction, as formulated by Stephen Kosslyn (e.g. Refs [19], [25], [28] and [53]). This work has revealed that categorical spatial relations are recognized more quickly and accurately in the right visual field (RVF) whereas coordinate spatial relations show a similar advantage for the left visual field (LVF). Laeng, in a recent study [31], has brought additional neuroanatomical evidence by showing that patients with unilateral posterior lesions had deficits in identifying and judging the similarity of categorical and coordinate spatial relations of visual stimuli. These findings mirrored the lateralization pattern exposed by the above mentioned studies with normal subjects. Specifically, left hemisphere patients had difficulty with categorical spatial relations whereas the right hemisphere patients had difficulty with spatial relations of the coordinate type. Moreover, in this study, there was evidence in support of the idea that the left hemisphere advantage in processing categorical relations cannot merely be due to the ability of this hemisphere to solve spatial tasks by verbal strategies: Aphasic impairment (i.e. a disruption of verbal mediation) did not correlate with the deficits in spatial perception.

Laeng’s study [31] yielded a more pronounced picture of lateral specialization than was evident in previous work [19, 22, 28, 51, 52]. While the clinical population may be partly responsible for the clear effects, it is also possible that the specific paradigm and stimuli used were especially effective in bringing out the asymmetries between hemispheres. For this reason, it seemed natural to ask whether such methods, applied to intact humans, would allow a clearer distinction between hemispheric specialization for categorical and coordinate operations than has been available to date.

Rather than using abstract and minimal stimuli (e.g. Ref. [19]), Laeng used drawings of animals or common objects which possessed a complex spatial structure composed of multiple surfaces and salient principal axes which featured natural distinctions between top and bottom, front and back and left and right sides (see Fig. 1 here for illustrations of some of the drawings). These objects can be presented in such a way that they may differ from each other in ways which are independent of their specific relation to an external observer. In other words, a spatial relation of the categorical kind can be based exclusively on the spatial frameworks defined by the objects themselves. For instance, two cats may be depicted at

identical distances to each other in two presentations, but in one case they face towards each other and in the other they do not. We reason that in order to achieve this description, the cognitive system prior to assigning specific categorical relations between the objects must analyze the spatial structure of the shape, a process that supposedly intervenes in its recognition (i.e. the assignment of a particular shape to a particular category). Consequently, spatial categorical encodings can be achieved by some rule that labels and matches the object's surfaces without the involvement of fine-grained quantitative analyses of the object's locations (i.e. coordinate information).

In contrast, we reason that for the description of coordinate spatial relations, shape analysis does not necessarily precede or take place together with the assignment to a spatial location of a physical "object". This assumption is based on evidence from the human [11, 17, 32, 37, 48, 63] and animal [62] literature that the processing of coordinate locations is independent of the processing of their shapes.

According to Kosslyn's model [25], the right hemisphere should be superior in detecting and encoding variations in the distance (coordinate) relations. The left hemisphere should be superior in encoding and processing variations in position that cause a category shift. These specializations can be easily dissociated, or independently tested, since we can create visual stimuli where the relative distance of the depicted objects varies without crossing of a category boundary, and, conversely, other stimuli where a category shift occurs without a change in relative distance of the objects.

In summary, we presented normal subjects with spatial recognition tasks involving transformations of the kind shown in Fig. 1. Subjects had to decide, and to indicate quickly, whether a pair of stimuli, shown in the right or left visual field, was the same or different from a previously viewed pair of stimuli. In keeping with Kosslyn's [25] model it was expected that right-handers (RHs) would show a double dissociation: For coordinate decisions, RTs for stimuli presented in the left visual field (LVF) would be faster than those for presentation in the right visual field (RVF), and the converse would be observed for stimuli involving categorical decisions.

EXPERIMENT 1

Methods and procedures

Subjects. Thirty-eight right-handed subjects were recruited from the undergraduate and graduate student population at the University of Michigan in Ann Arbor. Subjects were naïve to the purpose of the experiment other than the fact that it was an experiment on visual perception. They received a small amount of money in compensation for their participation. Half of the subjects tested were female (18–35 years of age; $M = 23.2$) and half were male (19–36 years of age; $M = 23.7$). Handedness was assessed with a modified version of the Edinburgh handedness questionnaire. Females and males did not differ significantly as groups in either age or handedness.

Apparatus. A T-IC Gerbrands two-field tachistoscope was connected to a Commodore 64 computer programmed to collect RTs (msec) of subjects from the onset of the tachistoscopic presentation. In the first field of the tachistoscope, a small black star, which served as a fixation point, appeared at the center. In the second field, pictures that differed from trial to trial were presented to the left or the right of the central star. In front of the subject, and below the rubber eyepiece of the tachistoscope, was a box with two response keys spaced 2.5 cm apart; the left key was for "same" and the right key was for "different" responses.

Stimulus material. Twenty pairs of color drawings consisting of an original sample figure and its match figure were used (cf. Fig. 1). The drawings depicted animals and common objects. The match figure was always a drawing of the same objects as in the sample figure. For half of the items the matching figure varied in terms of categorical relations while for the other half the matching figure varied in terms of coordinate relations. Eighty trials comprised the whole test. Each of the 20 drawings was paired once to its identical copy and once to its variant, and these 40 stimuli were shown once in each visual hemifield.

The following basic categorical spatial relations were included in the test items (see Fig. 1 for illustrations): Confrontation (e.g. left of/right of, in front of/behind; $n = 5$; these drawings always involved objects possessing

intrinsic sides, like animals, and were shown positioned on the same horizontal plane; see Fig. 1, panels A and B); Laterality (e.g. left/right; $n = 2$; this differs from the previous category because there is only one object depicted and shifts in left/right relations are relative to some third arbitrary point, e.g. the view-point or the frame's sides; see Fig. 1C); Verticality (e.g. above and below; $n = 2$; Fig. 1D); Inclusion (e.g. inside/outside, $n = 1$). The following coordinate relations were included in the test items: Distance on the horizontal axis ($n = 3$; see Fig. 1E); Distance on the vertical axis ($n = 2$); Distance in both axes ($n = 1$); Distance relative to the frame ($n = 1$); Position of body parts, $n = 2$; Fig. 1F); Object size ($n = 1$; Fig. 1G).

Possible biases in spatial frequency that may favor one hemisphere's performance regardless of the spatial relationships per se between the objects [22, 50] were avoided by creating an equal number of coordinate transformations in which the distance between the depicted objects would either expand or contract. A spatial frequency confounding would not occur in our categorical transformations since these never involve a change in the objects' relative distance or size.

Procedure. All stimuli were presented to the subjects according to a fixed random sequence. In other words, although items in every condition (task, visual field, etc.) were non-blocked, each individual subject received the items' presentation in exactly the same order. The subjects first viewed a sample stimulus card in free vision. No time constraint or specific instructions on what to look for in the drawings were given to the subjects. Subjects were simply asked to examine each drawing carefully before comparing its identity with another drawing viewed in the "tachistoscope". Subjects were instructed to quickly fixate the star at the center of the visual field, after viewing the first drawing, and to position the index finger of the right hand between the "same" and "different" key. At this point, the experimenter pressed a key that initiated the tachistoscopic presentation. The stimuli appeared for 150 msec at 6 degrees to the left or right of center. On average, the figures extended over 7 degrees of visual angle. Subjects had to depress either the "same" or "different" key as soon as they had made a decision. The RT and key that had been pressed were displayed on the screen and recorded on a score sheet by the experimenter. No feedback was given to the subjects about the correctness of their responses.

Before the actual testing began, a series of eight practice trials was performed to familiarize subjects with the procedures and the testing apparatus.

Scoring. RTs were adjusted by dividing the median RTs of "different" responses of each condition (i.e. spatial relation and visual field) by the median RTs to the "same" responses for these conditions and multiplying this proportion by the group mean of all RTs. RTs of wrong responses (i.e. the subject pressed the "same" key when the figures were different or the "different" key when they were the same) were excluded from these data. RTs longer than 2500 msec were also excluded. These adjustments were decided on the basis of both practical and theoretical reasons. In experiments with response time measurements it is often seen a wide range of differences in speed between individuals. If outliers are present (which in this case was true for both this experiment and the one following) it is easy to see the appearance of higher order interactions that are spurious, since a few outliers can distort medians and variances of a particular subgroup of subjects. Typically in psychological research, outliers are excluded, which has the disadvantage of excluding data that were actually collected. However, if the experimental design allows it, transforming each individual's scores relatively to their own baseline may take care of the problem and avoid neglecting subjects. In the case of the tasks described here, the "same" judgement of two physically identical stimuli offers such baseline. It is well-known that "same" judgements tend to be faster than "different" judgements (see Refs [29] and [47]) and particularly so if the stimuli are easily codable [6]. It is more theoretically relevant to know whether an individual shows a lengthening or shortening of RTs relatively to his/her own baseline (i.e. in the easier perceptual judgement), instead of taking the group's average value as the comparison. To offer an example, if we consider the performance of a subject that is generally very "slow" in making a "different" judgement in a specific visual field condition, he may likely fall within the range of a field "disadvantage" relatively to his group's average performance. However, he may actually show a clear RT advantage (or not such an abnormal disadvantage in another condition) when compared to his own baseline (i.e. the "same" judgement). It is when the effects are judged within the individual's performance itself that they are of particular theoretical interest, whereas raw scores compared to a group's average may be in specific instances quite meaningless and real effects confounded.

In addition to the RTs, the "errors", or the number of failures to notice the presentation of a "different" drawing, were counted for each subject and for each spatial relation and visual field condition.

Results

Response times. RTs were submitted to an ANOVA with Sex as between-subjects factor and Spatial Relation (categorical/coordinate) and Visual Field (left/right) as the within-subject factors. This analysis revealed a significant interaction (see Fig. 2) of the spatial relation and visual field factors [$F(1, 36) = 25.83$; $P < 0.0001$]. As predicted, RTs were faster for categorical transformations presented in the RVF ($M = 798$ msec; $S.E. = 25$) than in the LVF ($M = 923$ msec; $S.E. = 25$). A *post-hoc* comparison with a *t*-test showed that this difference was significant ($P < 0.0001$). As predicted, coordinate transformations yielded

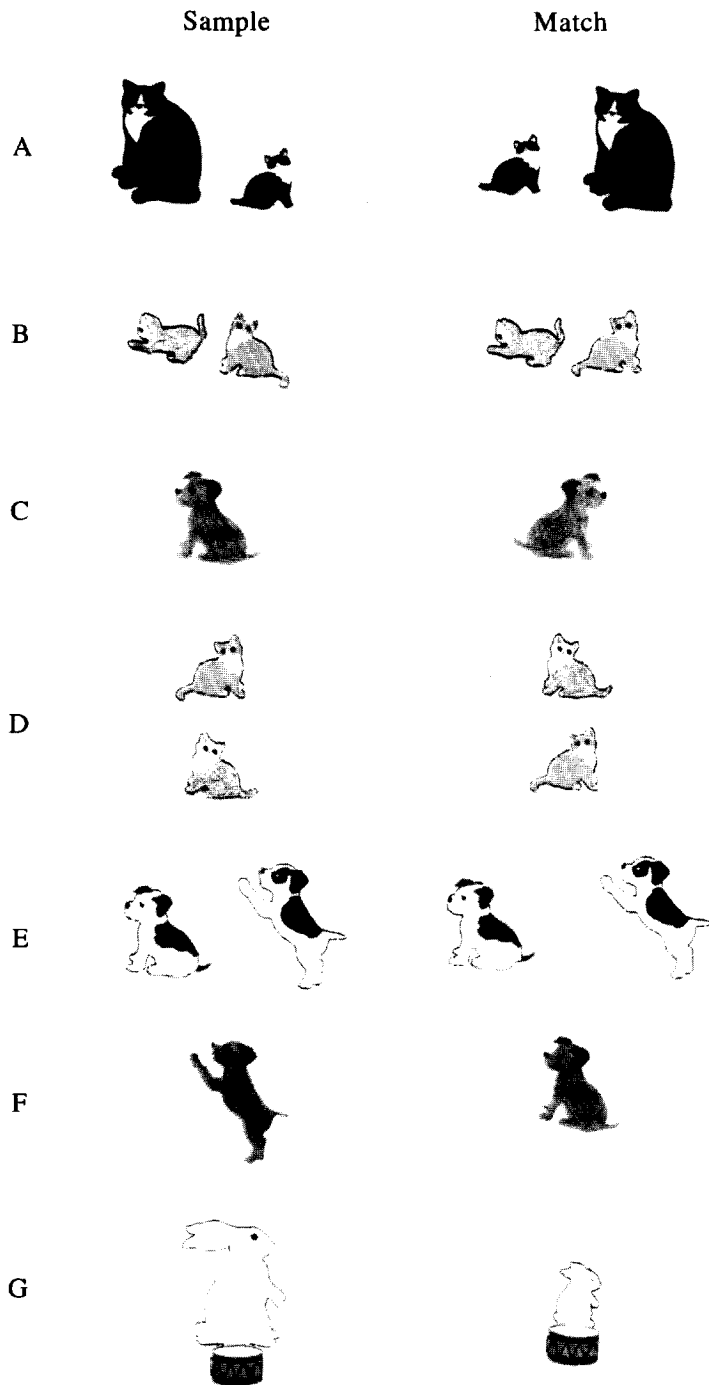


Fig. 1. Sample and match figure (left and right, respectively) of categorical spatial transformations (Panels A–D) and coordinate spatial transformations (Panels E–G).

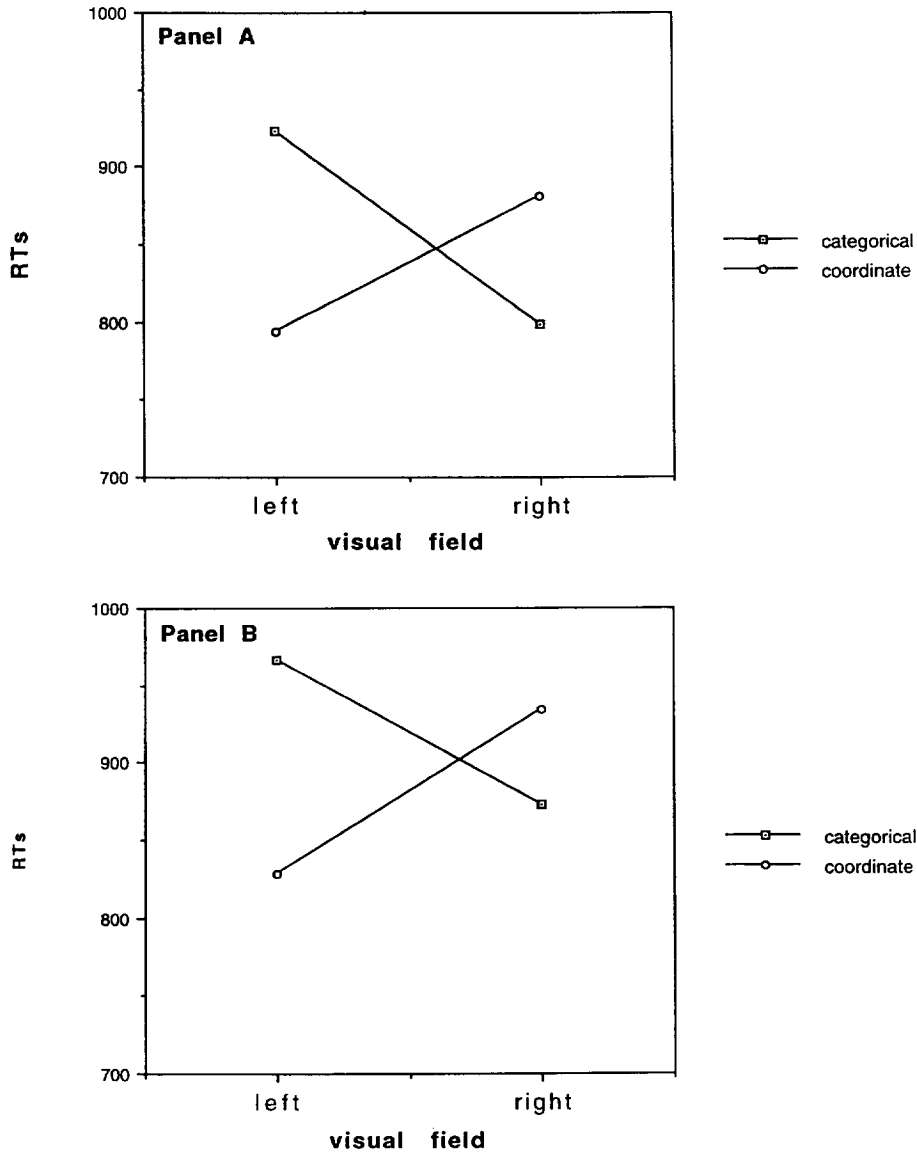


Fig. 2. Mean of RTs (in msec) in the *left* visual field and *right* visual field for items with transformations in *categorical* and *coordinate* spatial relations of right-handed subjects (Panel A: Experiment 1; and Panel B: Experiment 2).

faster RTs when presented in the LVF ($M = 793$ msec; $S.E. = 24$) than in the RVF ($M = 881$; $S.E. = 26$). A *post-hoc* comparison with a *t*-test showed that this difference was significant ($P < 0.004$). All other main effects and interactions were non-significant.

The effect size, in terms of percent of variance accounted for by the factors (Eta-squared, henceforth denoted as *ES*), and Power (based on an alpha of 0.05 throughout) were also calculated for the significant interaction of spatial relation and visual field: $ES = 0.42$; Power = 0.99.

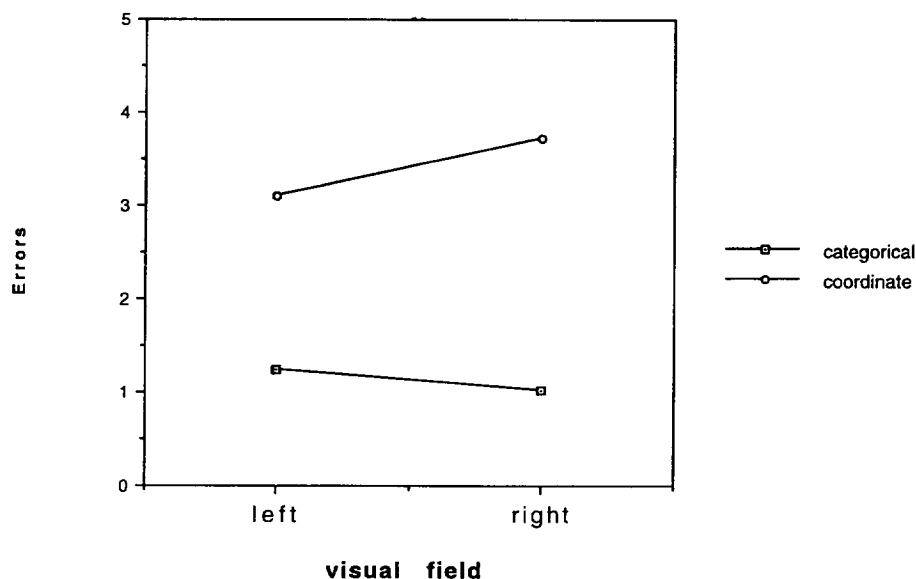


Fig. 3. Mean number of errors in the *left* visual field and *right* visual field for items with transformations in *categorical* and *coordinate* spatial relations in Experiment 1.

Errors. Subjects made more errors in categorical transformations in the LVF than in the RVF (see Fig. 3). The interaction effect for Spatial Relations and Visual Field was significant [$F(1, 36) = 8.29$; $P < 0.006$]. As predicted, a t -test showed that for the coordinate decisions the rate of errors was higher ($P < 0.004$) in the RVF ($M = 3.71$; $S.E. = 0.27$) than in the LVF ($M = 3.10$; $S.E. = 0.32$). For the categorical decisions, the overall rate of errors was very low for this condition and there was no significant difference ($P < 0.30$). The main effects of Sex and of Spatial Relation were statistically significant (Sex: [$F(1, 36) = 3.77$; $P < 0.059$]; Spatial Relation: [$F(1, 36) = 62.6$; $P < 0.0001$]). The sex effect was accounted for by a better performance of the female subjects (females: $M = 1.93$; $S.E. = 0.19$ males: $M = 2.60$; $S.E. = 0.23$). The Spatial Relation effect was accounted for by the larger number of errors made with the coordinate transformations ($M = 3.40$; $S.E. = 0.21$) than with the categorical ones ($M = 1.13$; $S.E. = 0.13$). All the other interactions were non-significant.

Correlation analysis of difference scores of RTs in the two visual fields for each spatial relation. A correlation analysis of the RTs was performed in order to assess whether the above seen hemispheric complementarity (captured by the Spatial relation by Visual Field cross-over interaction) would also hold at the individual level. In other words, it was assessed whether the observation in one individual of a certain degree of lateral advantage for one type of spatial relation would also tend to imply a similar but complementary advantage for the other spatial condition in this same individual. This would take the form of a negative correlation in the subjects' RT difference scores of the RVF and LVF for each spatial relation [19]. The small negative correlation ($r = -0.14$), was not significant. In fact, although 18 subjects of the 38 subjects showed the predicted RVF advantage for categorical relations and LVF advantage for coordinate relations, and only one subject showed the inverted pattern (but rather negligible visual fields' differences: Categorical = 21 msec; Coordinate = 40 msec), the remaining subjects either showed a LVF advantage ($n = 11$) or a RVF

advantage ($n=8$) for both conditions. Even after excluding those subjects who did not show a visual field difference of at least 100 msec (i.e. a subgroup of subjects who are likely to show individually a significant field advantage), the proportion of subjects showing the expected complementary visual field advantages remained identical.

Discussion

The findings support the idea that the two proposed types of spatial perception are lateralized in opposite hemispheres in a group of right-handed individuals. A significant proportion of the subjects showed the expected pattern of visual field advantages in the RTs: Correct judgements of the occurrence of spatial transformations were faster in the RVF for categorical spatial relations and in the LVF for coordinate spatial relations. Incorrect responses, which were excluded from the previous data, showed that the detection of a coordinate transformation was more likely to be inaccurate after RVF presentations whereas for categorical transformations more errors occurred after LVF presentations. The significantly higher rate of errors for the coordinate task than for the categorical task may have made it easier to reveal a statistical difference between the visual fields in the former case.

The symmetrical cross-over interaction in mean RTs (see Fig. 2, Panel A) showed that when the subjects were able to make a correct judgement (in other words, when they "saw" that something had changed in the drawing), the hemifield-dependent speed in expressing such decision was equally fast for the specialized task and equally slow for the non-specialized task. This finding may indicate that the processing time for making a correct perceptual decision is identical for each type of spatial relation. However, we must be cautious in drawing the above conclusion since error rate was different in the two spatial tasks and, therefore, these may have not been of the same difficulty. On the other hand, a look at the raw scores showed that the higher error rate of the coordinate task was mainly due to two particularly difficult items and it is possible that the remaining items were of equal difficulty with those in the categorical task.

Overall performance of the female subjects seemed to be slightly better than that of the males in terms of errors and RTs.

EXPERIMENT 2

In this second experiment a new group of subjects performed a modified version of the categorical/coordinate same/different task. The motivation for this experiment was to see whether the results for RHs could be replicated and whether left-handers (LHs) showed a comparable pattern of specialization. There are several reasons to suspect that handedness may be a factor in cerebral lateralization of spatial perception. Firstly, we posited that action is fundamental to spatial cognition [39, 41] and because LHs differ from RHs in several aspects of motor performance [44], the underlying cerebral specializations for space perception may vary with handedness. Secondly, there is convincing evidence from the clinical literature that unilateral brain lesions affect spatial performance differently in LHs and RHs [18]. Such evidence, collected largely with spatial tasks that require coordinate judgements, suggests that the cerebral organization of LHs is more "diffuse" (i.e. more cases of reversal of dominance or bilateral control) than that of RHs. Findings of experimental neuropsychological studies bring convergent evidence to this view [8]. The assumption of a

more diffuse cerebral organization leads to the prediction that such a group will be less likely to show a complementary pattern of specialization. Additionally, since there is evidence that LHs are not a homogeneous group in terms of motor lateral preference and performance [41, 42, 44], the analysis of LHs' performance took into account subgroups of left-handers.

Only one type of spatial category was used in the categorical task in this experiment. We selected the category in which patients with left-sided brain damage seemed to have the most difficulties [31]. This spatial category was labelled "confrontation", because in the drawings of these tests, variations in the way two animals face each other are depicted (i.e. whether the front, back, or one specific side of an animal is facing the other animal). Consequently, we expected this new task to be an even more powerful instrument in revealing left-hemispheric spatial competence.

Methods and procedures

Subjects. Sixty-six subjects participated in this experiment. They were all undergraduates (age ranged from 18 to 37) at the University of Guelph (Ontario) who were part of the undergraduate subject pool. Twenty-six subjects were right-handed. Only five of these subjects were male. Forty subjects were left-handed. Also for this group only five subjects were male. The asymmetry of sex ratios was of little concern because there had been no indication of significant interactions between sex, visual field and spatial relations in the previous work. Handedness was assessed with a nine-items questionnaire where the preferred hand is rated on a five-step scale (with a neutral midpoint indicating equal hand preference) for the following actions: write, draw, hammer, throw, toothbrush, use scissors, hold spoon, cut with knife, hold racquet. A subgroup of 13 "inconsistent" left-handed writers (ILHs) was characterized by a right-hand preference for throwing. The other subjects were classified as "consistent" left-handers (CLHs) if they preferred the left hand for the majority of activities, including writing and throwing, or as RHs if they were right-handed writers. The division of the left-handers in two subgroups is based on recent views on handedness (see Refs [40] and [44]) that indicate how left-handers may be better characterized by two groups of individuals with different performance skills. One group (the consistent left-handers) shows the reversed pattern of manuality of the right-handers. Another group shows a dissociation between strength and skill activities, which in turn may depend on two different developmental systems, a structural one (on which "throwing" or "holding a racquet" may rely upon) and an attentional one (on which fine distal hand/arm motor skills may rely upon).

Apparatus. Two carousel slide projectors were operated by a microcomputer. The computer also recorded RTs and errors. Slides were back-projected on a large translucent screen which also hid the electronic apparatus from the subject's view. Subjects sat at a small table positioned in front of the free side of the screen. An adjustable chin-rest was fixed to the table so as to stabilize the position of the head during each trial. The chin-rest was positioned so as to align the subject's midline to the fixation point (a small black star) appearing on the screen. Also fixed to the table and in front of the chin-rest was a little box with two keys spaced 4 cm apart and marked S (for "same") and D (for "different").

Stimulus material. As in the previous experiment, 20 pairs of color drawings were presented to the subjects. The sample figure was shown in free vision on a 7.5×12.6 cm card. The second figure, to be judged as same or different from the first one, consisted of a color slide of a drawing and was projected on the screen. Half of the categorical stimuli were identical to the ones used in the first experiment and the other half were newly designed. As in the previous experiment, eighty trials comprised the whole test.

Procedure. Stimuli were presented according to a fixed random sequence (but different from that selected in Experiment 1). Procedures were similar to those described earlier for Experiment 1 and differed only in the following aspects: After viewing the first drawing in free vision, subjects positioned their chin on the chin-rest and placed one finger of the left hand on the left key and one finger of the right hand on the right key (i.e. they used the spatially compatible hand for each key); subjects initiated the presentation by pressing one of the two keys on the response box; the stimuli appeared on the screen for 100 msec; the scores were automatically recorded by the computer. These procedures were selected after an unsuccessful pilot study, with somewhat different procedures, carried out with 12 RHs. Unlike the original study, where the sample stimulus cards were handed to the subjects, the entire procedure in the pilot study was automated. When the procedure was changed in keeping with the original methods, and subjects could inspect the sample cards in free vision, and without time limit, and when subjects were reminded throughout to focus on the fixation point, lateral asymmetries consistent with the original study emerged. The latter procedural detail is important because using a "tachistoscope" for fast presentations appears to make it easier for subjects to maintain focused on the central fixation point than does the back-screen projection method.

Scoring. The same scoring procedures used in Experiment 1 were applied. However, since subjects were divided into three handedness groups, separate overall RTs means were calculated for each group and used to adjust each subject's RTs to their group's average speed.

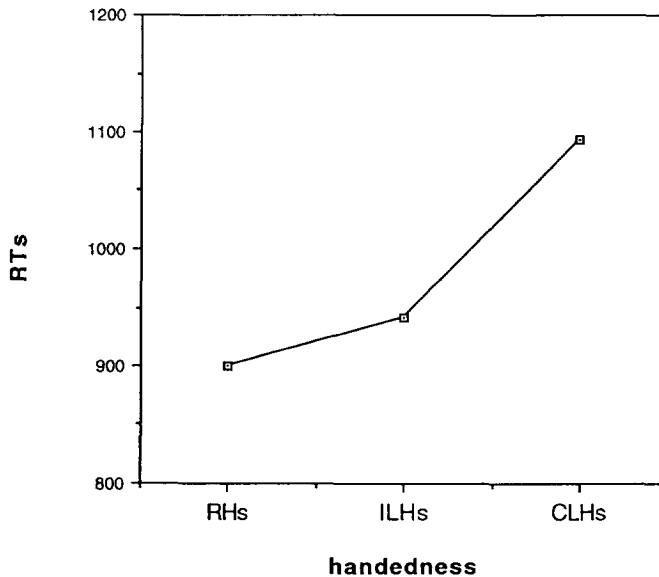


Fig. 4. Mean of RTs of each handedness group: right-handers (RHs), consistent left-handers (CLHs) and inconsistent left-handers (ILHs).

Results

Response times. RTs were analyzed with an ANOVA with Handedness (RHs, CLHs and ILHs) as between-subjects factor, and Spatial Relation (categorical/coordinate) and Visual Field (left/right) as the within-subjects factors. Sex was not included as a factor in the ANOVA since the number of males was too small in each handedness group.

This revealed a main effect of Handedness [$F(2, 63) = 11.88$; $P < 0.0001$], which was accounted by the slower performance of the CLHs ($M = 1094$ msec, $S.E. = 27$) compared to the ILHs ($M = 941$, $S.E. = 31$; Scheffe's S: $P < 0.01$) or the RHs ($M = 900$; $S.E. = 19$; Scheffe's S: $P < 0.0001$). See Fig. 4 for an illustration of these differences. This finding is not an artifact of the adjustment of the RTs since an ANOVA with the raw RTs shows the same effect [$F(2, 63) = 5.5$; $P < 0.006$].

The significant main effect of Handedness Groups prompted us to calculate the effect size of this difference between the CLHs and the RHs, because these groups had a similar number of subjects [$F(1, 50) = 23.38$, $P < 0.00001$; $ES = 0.32$; Power = 0.99].

Handedness as a factor interacted significantly with spatial relation and visual field [$F(2, 63) = 4.6$; $P < 0.01$]. Figure 2 (Panel B) shows the visual field by spatial relation interaction of the RHs, whereas Fig. 5 shows the same interaction for the CLHs and the ILHs. Below, we describe separate ANOVAs for each handedness group.

Errors. The ANOVA did not reveal any main effect or interactions. Consequently, errors were not further analyzed within each handedness group.

Right-handers. The analysis of RTs revealed a significant interaction of the Spatial Relation and Visual Field factors [$F(1/25) = 10.90$; $P < 0.003$, $ES = 0.32$, Power = 0.91]. Figure 2 (Panel B) illustrates this interaction. RTs were faster for categorical transformation presented in the RVF ($M = 873$; $S.E. = 34$) than in the LVF ($M = 967$; $S.E. = 34$). A *post-hoc* comparison showed that this difference was significant ($P < 0.02$). In addition, RTs were

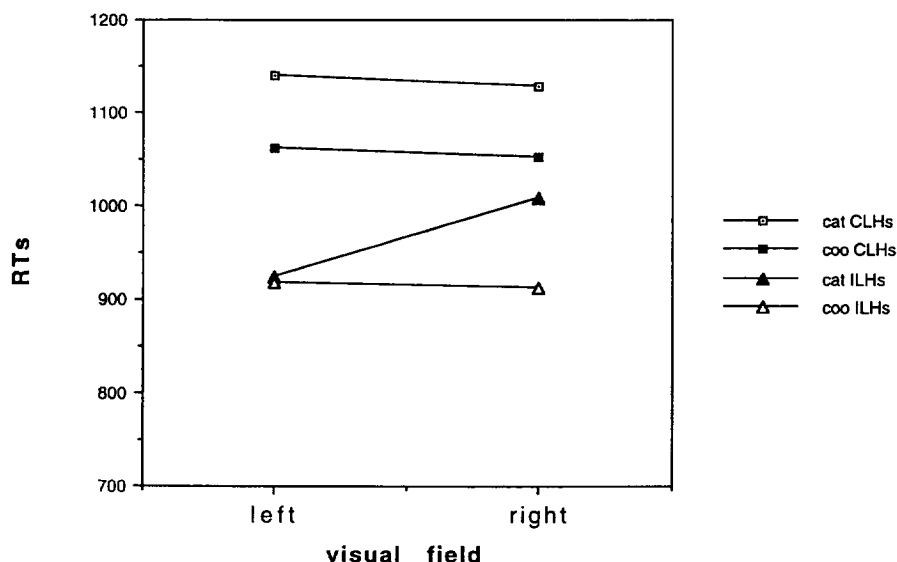


Fig. 5. Mean of RTs (msec) of consistent left-handers (CLHs) and inconsistent left-handers (ILHs) in the *left* visual field and *right* visual field for items with transformations in *categorical* (cat) and *coordinate* (coo) spatial relations.

faster for coordinate transformations presented in the LVF ($M = 828$; $S.E. = 35$) than in the RVF ($M = 934$; $S.E. = 42$). A *post-hoc* test showed that also this difference was significant ($P < 0.05$). The main effects of spatial relation and of visual field were not significant. These results provide a convincing replication of all the salient effects observed in Experiment 1.

Correlation analysis of difference scores of RTs in the two visual fields for each spatial relation. Fifteen subjects of the 26 subjects tested showed the predicted RVF advantage for categorical relations coupled with a LVF advantage for coordinate relations. Only one subject showed the inverted profile of field advantages, and while four subjects showed LVF advantages for both conditions, the remaining six subjects showed an overall RVF advantage. Moreover, the proportion of subjects showing the expected complementary pattern of field advantages remained identical after excluding subjects with less of 100 msec in a visual field difference. A correlation analysis, as seen before for Experiment 1, did not reveal significant correlations ($r = 0.16$).

Left-handers. The ANOVA of the CLHs' RTs revealed a significant effect only for the Spatial Relation factor [$F(1, 26) = 3.9$; $P < 0.05$]. This group of subjects found categorical judgements ($M = 1133$; $S.E. = 33$) harder than coordinate judgements ($M = 1056$; $S.E. = 31$).

The ANOVA of the ILHs' RTs did not reveal any significant effect.

Figure 5 illustrates the non-significant interaction of visual field by spatial relation for both left-hander groups.

Discussion

The group of RHs in this experiment successfully replicated the performance of the subjects in Experiment 1, where all subjects were right-handed. The interaction of spatial relation and visual field was again observed and the size of this effect (32% of total variance), although smaller than that of the previous experiment (42% of total variance) was of

comparable magnitude. Effect sizes in this range from 25 to 50% are considered of medium magnitude [10].

The RVF advantage for categorical decisions shows that a categorical task, where the relevant dimensions manipulated are constituted by relations emerging from using objects with lateral and frontal surfaces, is sufficient to fully reveal the specialization of the left hemisphere. However, our expectations of a greater sensitivity of this task were disappointed. Nevertheless, using a slide projection technique for laterality studies instead of the classical Gerbrand tachistoscope may have been a step down to a weaker experimental method which, therefore, may have obscured what could be gained with a more sensitive test.

The consistent performance of the RHs in this and the previous experiment also dissolves suspicions that using a specific hand for the response may have facilitated some of the lateral effects. In Experiment 1, subjects used only the right hand to press the keys, whereas in Experiment 2 the key corresponding to a "different" response was always operated by the left hand. These manipulations would have been expected to affect the results if the use of one hand really played some role in favoring speed for specific lateral presentations or spatial conditions.

Errors, as the dependent variable, failed to show any visual field difference for either condition. However, in contrast to patients with brain damage, intact individuals' error measures are less relevant than processing time (i.e. RT) since the latter measure more directly reflects the actual time it takes for the perceptual system to complete a specific operation [1].

Interestingly, the LHs appeared dramatically different from the RHs. Both left-handed groups differed from the right-handed group in that neither of the two showed a laterality effect for any of the two spatial conditions. These results are in agreement with Kosslyn's findings, based on a different task, in a group of undifferentiated LHs [25]. Moreover, the CLHs differed from both the ILHs and the RHs in that their overall performance in these spatial tasks was considerably slower. Although the difference between CLHs and ILHs should be taken with some caution due to the small number of ILHs, it seems clear that CLHs are about 200 msec slower in pressing the correct key than the RHs are.

We wish to make a final note about the fact that, despite the fact that we ignored the typical male-biased sampling of neuropsychological research (usually motivated by the idea that it is harder to show laterality effects with female subjects), by using in this experiment an almost completely female group of subjects, the findings were identical to the previous experiment where we had an equal representation of each sex.

GENERAL DISCUSSION

Space is undoubtedly one of the very basic forms of reality [23]. The possibility that multiple representations of space co-exist and cooperate in our knowledge and understanding of the world is present in several contemporary theoretical accounts (e.g. Refs [12], [33] and [38]). More often they have taken the form of dichotomies, like, just to name a few recent proposals: Kosslyn's [25] categorical/coordinate relations distinction (which is also coordinate to the neuroanatomical dichotomy of the cerebral hemispheres); Huttenlocher and colleagues' [21] model of a "fine-grained" and categorical ("prototypical" coding of spatial locations); Poucet's [46] hypotheses of different neural structures handling "topological" and "metric" information; or Turvey and Carello's [59] distinction of two complementary modes of functioning, a discrete ("symbolic") and a continuous ("dynamical") one. These

dual views of modes of perception all seem to indicate the existence of a qualitative, abstract and discrete, vs quantitative, "dense" [15] and continuous, representational forms. On one hand we observe the ability of the mind to discover the spatial relations that the physical presence of objects necessarily create in relation to each other. This constructive approach of the human mind (which may go back to Leibniz [57]) is relational because the objects themselves constitute the frames of reference (i.e. relations emerge between present objects and, therefore, unoccupied space is impossible). On the other hand, there is the need that acting with a material body in a material environment demands a spatial frame of reference that is three-dimensionally Cartesian, locally Euclidean, continuous, and extending in a vacuum. In both spatial representations, "the most pervasive and enduring constraints in the world in which we have evolved" [56] have been internalized, although the mechanisms of internalization (e.g. hard-wired in the nervous system or abstracted from experience; see Shepard [55]) may be rather different for different frames of reference.

Empirical evidence appears to support the view of dual codings. The neuropsychological evidence presented here and elsewhere [19, 28, 31] strongly suggests that separate functional subsystems process two types of spatial relations. The experiments reported here showed that robust and opposite visual field advantages, revealed by a tachistoscopic recognition task of lateralized displays, exist for spatial relations of the coordinate and categorical type (according to Kosslyn's [25] definitions).

In our two experiments, average response times and the difference between the RVF average response and LVF average response were remarkably similar in the two right-handed groups of subjects. For categorical judgements, the visual field's difference in response time was of 125 msec in Experiment 1 and, in Experiment 2 of 94 msec. Conversely, when subjects had to judge whether a transformation in coordinate spatial relations had occurred in our stimuli, the visual field differences in response times were of 88 msec in Experiment 1 and 106 msec in Experiment 2.

The similarity in the difference of processing times of the two spatial conditions (although their visual field advantages and disadvantages are reversed) in the two experiments is striking; and it may suggest that the encoding of the two spatial relations, as they apply to identical visual scenarios are of similar computational complexity. Also striking is the similarity in processing time for each spatial condition (averaged across visual fields); however, this is most likely the result of similar difficulty levels of the two types of spatial recognition problems. The visual field differences in RTs in our experiments showed a rather different range from those reported in previous studies: In our study, they ranged from 88 to 125 msec (about 100 msec in processing time were gained when a specific spatial transformation was presented first to the specialized hemisphere); whereas in Kosslyn's *et al.* [28] series of experiments, RTs differences were, on average, 57 msec; in Hellige and Michimata's [19] study and Servos and Peters' [53] studies, RTs differences were even smaller (about 12 and 16 msec, respectively). This variability across studies in the RTs' difference between visual fields may be accounted for by differences in the depth of analysis required by the different visual stimuli used and by the degree of internal consistency of the tasks (i.e. amount of invariant rules, components, informational sequences, that the processing of the stimuli implies for the subject). Stimuli used in past studies consisted of colorless two-dimensional figures whose intrinsic spatial structure is very minimal, whereas in the experiments presented here stimuli were colored and fairly detailed depictions of three-dimensional real (meaningful) objects. Additionally, the previous studies required subjects to identify examples belonging to a single and explicitly pre-determined dimension for each

categorical or coordinate spatial relation (e.g. above or below, near or far). In our experiments, spatial relations varied across several dimensions for each spatial relation and were randomly intermixed in a single session. Task demands of this present study also explicitly required holding the sample figure actively in visual memory, in order to compare it to the tachistoscopically-presented one. This last additional cognitive task may have specifically contributed to the strong differences of the RTs to the hemifield presentations and the robustness of the observed effects [36].

The complementary pattern of visual field advantages clearly showed by the RHs leads us to conclude that the two hemispheres are, as hypothesized, differentially specialized in the processes underlying the perception of the two kinds of spatial relations; which, additionally, provides evidence for the existence of distinct processing systems [54]. In fact, if a single system were responsible for the perception of both types of spatial relation, the RTs scores could have not "double-dissociated" in a complementary manner as it was observed here with the RHs' performance.

We cannot fully discard the possibility that at the basis of part of these findings there may be a non-spatial factor or strategy. It may seem a more economical interpretation to view the RVF advantage for categorical relations as showing that these spatial relations, which are easily labelled verbally (by prepositional locatives, for instance), may benefit from a purely verbal strategy (which, supposedly, is a left hemispheric competence). According to this view, spatial relations seen in the sample figure are first labelled, and this verbal label (e.g. "a black cat to the left of a white cat") is held in verbal memory, to be later compared for its semantic identity to a new verbal label applied to the match drawing. It is assumed that such strategy may be advantageous if its operations (encoding, retrieval and comparison procedures) are processed faster than parallel operations performed in visual memory (i.e. the purely spatial strategy). However, we do not possess any specific evidence to believe that such left hemispheric verbal mediation operations are underlying these results (and that the assumptions on which it is based are correct). On the contrary, the clinical study with unilateral stroke patients [31] suggested that verbal mediation may not underlie the left hemisphere's competence for the perception of spatial relations; since the degree of aphasia did not correlate with the degree of deficit in identifying transformations in categorical spatial relations. Additionally, computer simulations like those of Kosslyn and colleagues with split connectionist networks [27] rule out in principle that the mediation of language is necessary to obtain such dissociations. In fact, the real question is if and to what extent some subjects use verbal mediation in categorical spatial tasks. It is also important to remark that possessing a verbal label does not necessarily imply that even those tasks that require explicitly to produce a verbal label will result in a left hemispheric effect. To this point, an experiment by Berlucchi and colleagues [5] shows that when subjects are required to name the time on a clock face shown tachistoscopically in one of the two hemifields, there is still a LVF advantage in RTs. In the perspective offered here, it would be expected that various orientations of the hands on a clock would not always correspond to perceptual categories of orientations, and therefore their reading depend heavily on the right hemisphere's metric skills, whereas (in the study by Umiltà *et al.* [61]) responding to lines in categorical positions (horizontal and vertical meridians and 45° slants) would be faster after presentations to the left hemisphere.

In summary, we prefer to interpret these results in line with current ideas about a perceptual dual coding of spatial relations. Kosslyn [25] has posited that categorical spatial relations are encoded by perceptual (sensory) categories in which positions are grouped on

the basis of a single attribute, differently from coordinate spatial relations that encode “metrically” spatial positions. In this view, categorical perception evolved to represent those objects’ attributes that are for the perceiver significant invariant properties. Perceptual categories are based on an abstraction process that ignores variations within specific boundaries. The boundaries may correspond to the “pervasive and enduring constraints of our world”. In these percepts, a whole sensory region is a discrete and labelled equivalence class [16].

An example of what is meant in the above paragraph is given by the spatial relation referred in language with the prepositions of “inside” and “outside”. Objects seen across a boundary are “directly” perceived as being in a bounded (inside) or boundless (outside) region of space. We are not implying here that behind such directness of perception there may not be rather complex algorithms and computations (see Ullman’s [60] discussion of the inside/outside relation); but it seems clear to us that being able to verbally name objects as inside or outside is more an example of language reflecting what our perceptual system can do [9, 14, 30] than the other way around. As Kosslyn and Koenig [26] propose, the visual spatial system has adapted to perceive “categorically” in order to solve some specific perceptual problems (e.g. “the Contorted Person Problem”, or the fundamental recognition problem of identifying an object, like a person, when its parts are seen in novel ways). Coordinate spatial encodings will originate from a different selective pressure, that is the necessity for a biological organism to navigate its self-ambulating and articulated body in a physical world.

The question remains of why categorical spatial perception appear to mainly depend on the left hemisphere of the brain; a neuroanatomical finding that is in contrast with the well-known specialization for spatial perception of the right hemisphere. The contrast with the “doctrine” of right hemisphere’s dominance for spatial processing is probably simply explained by the fact that virtually all the doctrinal evidence (see also Ref. [31]) is based on experimental manipulations of coordinate perceptual problems. However, some theoretical considerations can be made in favor of the occurrence of a cerebral functional “cleavage” of spatial perceptual abilities. Kosslyn [25] has hypothesized that the left hemisphere may contain the “seed” for the development of speech and along with it, following a principle of functional economy, of several classes of categorical processing. An additional factor reinforcing the close proximity of mechanisms supporting different categorical functions as speech and spatial perception stands in the fact that categorical processing is at the basis of our recognition processes (i.e. the partition of the world in classes of objects), and that the identity of objects and how they relate to each other constitute an essential part of our inter-individual communications. The proximity or co-existence in one hemisphere of the cerebral loci committed to communication and perceptual categorization seems to be a rather optimal design. Additionally, two distinct but closely related input/output mappings would benefit from neural distance (by reducing interference; e.g. Refs [24] and [27]), and categorical and coordinate mappings were postulated as different outputs of the same visual input.

Finally, the so far described “division of labor” between the two hemispheres for spatial perception has to be discussed in the light of the fact that although this picture seems to hold true for the majority of people (i.e. the RHs), it is not true for all. However, a negative finding in experiments searching for hemispheric advantages is particularly difficult to interpret (certainly more than a positive finding), because it cannot be taken at face value as an indication that the hemispheric organization of an individual is really different (or, as well, of

a group of individuals similar along some attribute; e.g. sex, handedness). Several factors may contribute to confounding in experiments with normal subjects (e.g. different attentional capacities or strategies in processing the stimuli; see [24] and [43]) so as to make functional laterality measures (i.e. divided fields studies or dichotic listening) less sensitive than lesion studies in revealing lateralization of function; see Refs [7], [13] and [45]. If evidence from clinical cases with brain damage is more direct and clear-cut, the now available clinical evidence [31] of unilateral lesions on spatial relations task has been conducted only on a population of RHs; and, therefore, it is not known whether the same lesions would affect LHs differently. However, it is suggestive that Hecaen ([18], see also Ref. [49]) and his colleagues have shown that for spatial tasks (that we may define as "coordinate" tasks), LHs show a more variable, diffuse or bilateral organization of the cerebral hemispheres. It may then not be wrong to take the tachistoscopic findings as indicating true individual differences in cerebral organization (that are more or less likely to appear in a specific handedness group). Although it may be a premature conclusion, the significant difference in overall speed in the spatial tasks of the CLHs compared to the RHs may reflect the differential effectiveness of the distribution of the relevant computational loci or, in other words, how lateralization influences performance in these tasks. It is intriguing that the effect size (Eta-squared) of the lateral advantages demonstrated by the RHs (Experiment 1: $ES=0.42$; Experiment 2: $ES=0.32$) and the effect size of the difference in RTs of RHs and CLHs (Experiment 2: $ES=0.32$) are very similar. It seems to suggest that there is a certain processing time advantage due to hemispheric specialization that is lost by subjects that have more symmetric functional organization.

Additionally, the significantly slower performance of the LHs in a categorical task that involved exclusively transformations on the horizontal plane of the relative orientations of the objects' sides (e.g. left/right shifts of position) may suggest that this type of spatial judgement is harder for them than for the RHs. Benton [3, 4] has suggested that the readiness to recognize and avoid confusion between left and right is dependent on the degree of motor asymmetry. Several genetic theories of handedness (e.g. Annett's [2]) view LHs as a group comprising individuals who do not have a specifically predetermined asymmetry in motor control. Several authors (e.g. Refs [20] and [58]) have also proposed that deciding the "handedness" of shapes requires seeing which of their parts correspond to our left and right sides. In other words, the spatial structural descriptions of shapes may have to be "aligned" to an egocentric system of left and right in order to define the categorical relations between the objects. On the basis of all of the above considerations, LHs would be expected to show, compared to RHs, a difference in the readiness for decisions about categorical spatial relations that involve encoding the handedness of shapes.

Acknowledgements—The authors thank Drs Charles M. Butter and Henry (Gus) Buchtel at the University of Michigan for their comments and advice on the first experiment. Thanks also go to Dr Dan Weintraub for kindly providing the Gerbrand tachistoscope and to Tahki Jayasvasti for some of the data collection.

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