Article Author: Kosslyn

Article Title: Evidence for two types of spatial representations: Hemispheric specialization for categorical and coordinate relations

Call #: BF1 .J613

Location: evans

Not Wanted Date: 02/19/2006

Status: Faculty
Phone: 845-2503
E-mail: tya@psyc.tamu.edu

Name: Yamauchi, Takashi

Pickup at Evans

Mail Stop 4235
Dept. of Psychology
College Station, TX 77843
Evidence for Two Types of Spatial Representations: Hemispheric Specialization for Categorical and Coordinate Relations

Stephen M. Kosslyn, Olivier Koenig, Anna Barrett, and Carolyn Backer Cave
Harvard University

Joyce Tang
University of California, Berkeley

John D. E. Gabrieli
Northwestern University

Analyses of human object recognition abilities led to the hypothesis that 2 kinds of spatial relation representations are used in human vision. Evidence for the distinction between abstract categorical spatial relation representations and specific coordinate spatial relation representations was provided in 4 experiments. These results indicate that Ss make categorical judgments—on/off, left/right, and above/below—faster when stimuli are initially presented to the left cerebral hemisphere, whereas they make evaluations of distance—in relation to 2 mm, 3 mm, or 1 in. (2.54 cm)—faster when stimuli are initially presented to the right cerebral hemisphere. In addition, there was evidence that categorical representations developed with practice.

Different representations make different information explicit and, hence, are useful for different purposes. This principle has been particularly important in research on computer vision, in which distinct representations are used in different phases of visual information processing (e.g., Feldman, 1985; Marr, 1982). However, surprisingly little is known about the specific representations that are used in many aspects of human vision. In this article we consider the possibility that two distinct types of representations are used in one aspect of vision, the encoding of spatial relations. The hypotheses we considered were formulated on the basis of computational analyses and were then tested using logic and methods from neuropsychology.

Computational analyses typically begin with a behavioral test that must be exhibited by a processing system. In the case of vision, it is fairly easy to characterize such abilities by observing the conditions under which vision successfully guides behavior. Consider, for example, the fact that we can recognize a dog when it is curled up asleep, sitting for a bone, or running across a field. The shapes projected in these different situations are radically different, but we nonetheless can map them into a common representation in memory. This ability is what rules out simple template theories of perceptual recognition; a single template will not be able to match these varied shapes (Risser, 1967).

In thinking about how to build a machine that exhibits this behavior, then, one must analyze the input in such a way that one can abstract what information is available to perform the task. It is useful to begin by observing what kinds of properties remain constant as a semirigid object—such as a dog, a pair of scissors, or a bicycle—undergoes contortions: First, no parts are added or deleted (although some may be obscured in some configurations). Second, the spatial relations among the parts remain constant if they are characterized at a sufficiently abstract level of description. Certainly, the topological relations remain constant under the various transformations of semirigid objects. Parts remain connected or disconnected in the same way, and parts remain inside or outside the object. For example, in the case of the dog, the foreleg remains connected to the upper leg, no matter what the posture of the dog, and the eyes remain inside the face and the ears remain outside the face, no matter what its expression.

However, topological relations per se fail to draw many important distinctions; for example, a teacup and a phonograph record have identical topological descriptions (because each has a single hole). Other, more restrictive, sorts of abstract relations remain constant under contortions of semirigid objects, such as dogs, scissors, bicycles, or humans. For example, no matter how a person is contorted, the ears remain at the side of the head, the nose is always on the front of the face, and the arms remain connected at the top and to either side of the torso. A description using such abstract relations will remain constant as the object contorts and hence will be useful for recognizing the object in a variety of circumstances.

In many cases, then, it is useful to describe the relations among parts in abstract terms, using relations that are more restrictive than those specified by topological descriptions. These categorical representations capture general properties of the spatial structure without making commitments to the specific topographic properties that are likely to change from instance to instance. These relations are categorical in that they assign a configuration to a fairly broad equivalence class, the members of which share only some general characteristics. For example, two objects can be left of another object even

This work was supported by Air Force Office of Scientific Research Grant 880012, which was supplemented with funding from the Office of Naval Research (awarded to the first author) and by Fellowships 88.357.0.86 from the Swiss Science Foundation (awarded to the second author). We wish to thank Jean Ray for technical assistance. Correspondence concerning this article should be addressed to S. M. Kosslyn, Department of Psychology, 1236 William James Hall, Harvard University, 33 Kirkland Street, Cambridge, Massachusetts 02138.
though they differ widely in their locations on vertical and horizontal axes.

However, the virtues of categorical spatial relation representations for recognizing semirigid objects are drawbacks for accomplishing other types of behavior. Consider another ability of the visual system: One can view a gap between two rocks and decide whether the space is big enough to put one's foot in, or one can reach to a paper clip on a tabletop, or one can recognize whether someone has moved one's purse by noticing whether the strap is misplaced in relation to the bag. In all of these cases, categorical relations would not help the system detect the relevant variation. Indeed, in recognizing a face seen very close up, categorical relations would be useless. Everyone has eyes that are next to each other and above the nose. In these cases, one needs to know more precise, metric information about how objects and parts are positioned in space. A coordinate representation must be used in which locations of objects or parts are specified relatively precisely in terms of metric units.

Representations are produced by processing subsystems, with each subsystem corresponding to a set of neurons that work together to transform input into a specific type of output. The greater the difference is in the mapping from input to output in two cases, the more likely it is that separate subsystems perform the transformations. Thus, because categorical and coordinate representations are qualitatively different, one can hypothesize that separate processing subsystems produce each type of representation. However, although it would be awkward to construct, it is possible that a single subsystem produces both types of representations. We need to derive predictions from the distinction between the two types of representations and to conduct empirical tests.

One convenient way to garner evidence for the distinction between categorical and coordinate spatial relations representations rests on findings in neuropsychology, which provide clues regarding possible differences in the cerebral localization of categorical and coordinate processing. Perhaps the least controversial finding in all of neuropsychology is that the left cerebral hemisphere is critically involved in language processing in right-handed people (e.g., see Hecaen & Albert, 1978; Kolb & Whishaw, 1985). Furthermore, important aspects of language processing are known to have categorical properties (e.g., Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967). Indeed, there is evidence that even newborn infants are sensitive to categorical features of language (e.g., Eimas, Siqueland, Jusczyk, & Vigorito, 1971). We conjectured that because much of language hinges on the formation of categories of various sorts, the left cerebral hemisphere may be suited for categorical processing in general, including that used in visual spatial perception. In contrast, there is evidence in the clinical literature that the right cerebral hemisphere is essential for navigation (e.g., De Renzi, 1982; Hecaen & Albert, 1978; Kolb & Whishaw, 1985). It is clear that coordinate representations are critical for navigation: One needs to know more than that an object is next to a wall in order to reach it; one needs to know exactly where it is along the wall. If so, we reasoned, then the right cerebral hemisphere might be more adept at using coordinate spatial relations because they provide necessary input to the navigation system for a more detailed explication of these and related ideas, see Kosslyn, 1987).

For present purposes, the important consequence of our hypotheses about hemispheric specialization is that if they are correct, then we have evidence for the existence of two distinct processing subsystems, each of which is specialized for computing a particular type of representation of spatial relations. That is, if there is a relative left-hemisphere advantage for processing categorical relations and a relative right-hemisphere advantage for processing coordinate relations, then we will have evidence that the brain respects the distinction between the two types of representations. If only a single type of representation were produced, it would be processed better in one hemisphere or equally effectively in both hemispheres.

Thus, in this article we report a series of experiments that demonstrate a dissociation in processing of categorical and coordinate spatial relations. These experiments make use of a divided visual field methodology to ensure that one hemisphere has exposure to a stimulus before the other. If one hemisphere is in fact superior at a specific kind of processing, then there should be better performance when the task is presented to it initially than when the task is presented to the other hemisphere initially (Beaumont, 1982; Bryden, 1982; Springer & Deutsch, 1981).

Experiment 1

A hallmark of categorical spatial relations is that a set of positions are grouped together and treated as equivalent. For example, a cup is on a table no matter where on the top it rests; for purposes of assigning the relation, the differences in position are ignored. Thus, the judgment of on versus off is a clear case in which a categorical relation is used. In contrast, if we asked a person to decide whether a cup was within a foot of the edge of the table, a categorical relation would no longer be sufficient; in this case, the actual metric relations must be computed and used to make the judgment.

Experiment 1 used analogues of these two tasks, requiring subjects to decide whether a dot was on or off the contour of a line drawing of a blob (the on/off task) or whether a dot was within 2 mm of the contour (the distance task). The stimuli were presented briefly to the left or right visual field, ensuring that each stimulus was initially seen in only one hemisphere.

We expected to find faster judgments when the stimuli were presented initially to the left hemisphere in the on/off task and faster judgments when the stimuli were presented initially to the right hemisphere in the distance task. If we did, this would constitute evidence supporting the distinction between the two kinds of spatial representations.

Method

Subjects. Twenty-four right-handed Harvard University students volunteered to participate as paid subjects. In this and all subsequent experiments, all subjects reported having normal or corrected-to-normal vision. No subject participated in more than one of the experiments reported in this article, and no subject was aware of the purposes or any of the experimental figures with which they were not familiar.

Materials. The figure used also included a row of 10 dots representing 10 different fixation points. The distance task had a row of 10 fixation points at the right side of the page. In the dot on versus dot off task, the dot on and off condition varied from the figure to the right side of the page. The dot on and off condition were each presented 10 times, for a total of 20 trials, and separated by a 10-s interval.

The same set of distances was used for the dot on versus dot off task, with 0, 1, 2, 3, 4, 5, 6, 7, 8, and 9 mm from the dot on and dot off condition. These conditions were each presented 10 times, for a total of 20 trials, and separated by a 10-s interval.

A standard L-shaped rubber eyepiece was used to present the stimuli in a horizontal distance of 0.5 cm from the center of the fixation point. The stimulus was a cross with a millisecond SAT dot in the middle of the stimulus being pressed. On (or off) trials, the dot on the cross was turned on (or off) by pressing the SAT button (depending on the condition).

Procedure. Subjects were split into two groups and half were presented with each task. Half of the women were tested on the dot on versus dot off task with a sheet of type that varied with each run. Subjects were tested on the dot on versus dot off task first, followed by the dot on and dot off task. These subjects were then tested the following week on the dot on versus dot off task first, followed by the dot on and dot off task. Subjects were tested on the dot on versus dot off task first, followed by the dot on and dot off task. These subjects were then tested the following week.
that a set of univalent. For on the top if it differences in versus off is a l. In contrast, was within a led would no metric relations ent. hits, requiring the contour of whether a dot cce task). The a visual field, in only one stimuli were on/off task cted initially f we did, this tion between

Student students all subsequent or corrected-toan one of the us aware of the

purposes or predictions of the experiment at the time of testing in any of the experiments reported here.

Materials. The stimuli for the two tasks were amorphous outline figures with a large dot located 0, 1, or 10 mm from the border of the figure. The figures were drawn in black ink on white cards. Each card also included a central fixation point, which was 5 mm in diameter, equivalent to 0.32° of visual angle. The figures subtended approximately 1.6° of visual angle (25 mm in diameter), and the accompanying dots subtended approximately 0.26° of visual angle (4 mm). The figures were placed with the most central edge 2° from the fixation point, with half being placed to the left and half being placed to the right of the fixation point.

In the distance trials, which should require the representation of coordinate spatial relations, there were 10 stimuli with the dot 10 mm from the figure, 5 with the dot 1 mm from the figure, and 5 with the dot on the border of the figure. Those cards with dots 10 mm from the figure were designated as far and the others as near, making 10 different far stimuli and 10 different near stimuli. The stimuli were each presented a second time, in a second set of 20 trials; thus there were a total of 40 trials.

There were an equal number of near and far trials on which the stimulus was left of the fixation point and on which it was right of the fixation point. However, because the near stimuli were divided between 1-mm and 0-mm distances, for each of these subclasses there were only five instances. This meant that 1- and 0-mm trials could not be perfectly divided between the first and second halves of the trials, and so these trials were divided as equally as possible.

The same stimulus cards were used in the on/off task as in the distance task, except that half of the 10-mm stimuli were changed to 0-mm, ensuring that there were an equal number of stimuli with the dot on and off the contour of the blob. The dots appeared equally often in each quadrant of the blobs. Examples of the stimuli are presented in Figure 1.

A Scientific Prototype Manufacturing Company tachistoscope was used to present the stimuli. Subjects sat with their foreheads against a rubber eyepiece that kept their heads positioned at a constant distance from the screen. Two telegraphic keys were attached to a millisecond-accuracy clock, which was started by the presentation of the stimulus. The clock was stopped when either of the keys was pressed. One key was labeled on or near and the other off or far (depending on the task).

Procedure. Half of the subjects were tested in the distance task, and half were tested in the on/off task; equal numbers of men and women were assigned to the two groups. The two tasks were conducted under identical conditions. First, the subjects were given a sheet of typed instructions, which they read and then repeated to the experimenter. Any misunderstandings were corrected at that time. Subjects in the distance task were asked to judge whether the dot was within 2 mm of the contour of the blob; they were explicitly told that dots falling on the border were to be treated as within this limit. These subjects were shown what a 2-mm distance looked like in the tachistoscope, with two dots being so positioned. Subjects in the on/off condition were asked to judge whether the dot was on or off the contour of the blob.

Next, the subjects were given six practice trials (two 0-mm trials, two 1-mm trials, and two 10-mm trials) with feedback about their accuracy. At the end of these trials, the subjects were asked whether they thought they were ready to go on. The ones who replied affirmatively then received the test trials. About one fifth of the subjects wanted more practice; most of these were in the distance judgment condition. These subjects were given additional pairs of practice trials until they reported feeling confident in their answers, at which point they received the test trials.

The trials began with a fixation point that was visible for 5 s, followed by a stimulus that was visible for 125 ms. The interstimulus interval (ISI) was approximately 2 s, although there was no exact ISI because the cards were replaced by hand. The trials were presented in a random sequence, except that no more than three consecutive trials could have the same response or appear in the same visual fields. No feedback was given during the experimental trials. After the first 20 trials, there was a short (approximately 1 min) break.

Subjects positioned the index finger of one hand on one key, and positioned the index finger of the other hand on the other key. Half of the subjects were asked to respond with on or near using the right hand and off or far using the left hand, and vice versa for the other half of the subjects. The overhead lights in the room were turned off, leaving only the light from a small incandescent table lamp placed behind the tachistoscope near the experimenter (who needed the light to record the responses). The experimenter and clock were behind the tachistoscope. Subjects were asked to respond as quickly as possible while being as accurate as possible.

Results

The response times were considered in an analysis of variance (ANOVA). Prior to computing mean response times for each condition for each subject, trials on which errors had occurred were removed. The first analysis included task, hemisphere, gender, hand of "yes" response (on or near, depending on the condition), and response as independent variables. For these and all other analyses reported in this article, all effects and interactions not mentioned were not significant (p > .01 in all cases); however, we occasionally note such nonsignificant effects when they are of theoretical interest.

The results of primary interest are illustrated in Figure 2. As is evident, on/off trials were evaluated faster when they were presented initially to the left hemisphere (in the right visual field), whereas near/far trials were evaluated faster when
they were presented initially to the right hemisphere (in the left visual field), F(1, 16) = 15.59, p = .001, MS<sub>E</sub> = 0.01041, for the interaction of task and hemisphere. Contrasts examining the simple effects revealed that response times were faster when trials were presented initially to the right hemisphere in the distance task, F(1, 16) = 13.69, p < .01, MS<sub>E</sub> = 0.01041, but there was only a marginal advantage when trials were presented initially to the left hemisphere in the on/off task, F(1, 16) = 3.61, p < .1, MS<sub>E</sub> = 0.01041. The only other effect or interaction even to approach significance reflected a tendency for more time to be required in the on/off task, F(1, 16) = 3.15, p < .1, MS<sub>E</sub> = 0.20099.

The subjects were very accurate in general, and there was no speed-accuracy trade-off in these data. An analysis of the error rates revealed that the on/off task was more difficult than the distance task (with errors of 3.3% and 1.6%, respectively), F(1, 16) = 4.74, p < .05, MS<sub>E</sub> = 0.635417. In addition, when the left hand was used to respond near or on and the right hand was used to respond far or off, there were more errors when stimuli were presented initially to the right hemisphere (3.3% vs. 8.8% for left- and right-hemisphere presentation, respectively), whereas when the hands were reversed, there were more errors when the stimuli were presented initially to the left hemisphere (4.6% vs. 2.9%), F(1, 16) = 4.74, p < .05, MS<sub>E</sub> = 0.635417, for the interaction of hemisphere and hand countering group.

An additional analysis was conducted to examine only the stimuli that were identical in the two tasks. (Recall that half of the on stimuli also served as near stimuli and half of the off stimuli also served as far stimuli.) Again, the time to perform the tasks depended on which hemisphere initially received the stimuli, F(1, 16) = 33.24, p < .001, MS<sub>E</sub> = 0.00338, for the interaction between task and hemisphere (with means of 0.915 and 0.989 s for the on/off task and of 0.823 and 0.760 s for the distance task when stimuli were presented initially to the left and right hemispheres, respectively). Contrasts examining the simple effects revealed an advantage of presenting the stimuli initially to the right hemisphere in the distance task, F(1, 16) = 14.19, p < .01, MS<sub>E</sub> = 0.00338, and an advantage of presenting the stimuli initially to the left hemisphere in the on/off task, F(1, 16) = 19.23, p < .001, MS<sub>E</sub> = 0.00338. In addition, we found that men responded near or on faster than far or off, whereas there was no difference for women, F(1, 16) = 5.60, p < .05, MS<sub>E</sub> = 0.01468, for the interaction of response and gender; furthermore, the near or on responses were faster than the far or off responses when stimuli were presented initially to the left hemisphere, and vice versa when they were presented initially to the right hemisphere, F(1, 16) = 11.04, p < .005, MS<sub>E</sub> = 0.005152. The only marginal effect of interest was a tendency for slower responses overall for the on/off task, F(1, 16) = 3.64, p < .05, MS<sub>E</sub> = 0.16842. Finally, there were so few errors for these stimuli that they preclude meaningful analysis.

**Discussion**

As predicted, subjects performed the on/off task faster when stimuli were presented initially to the left hemisphere, but they performed the distance task faster when stimuli were presented initially to the right hemisphere. This was true both for the entire data set and for only the stimuli that were used in both tasks. In addition, these findings were obtained for both genders. Thus, we have preliminary evidence supporting the psychological reality of two distinct ways of representing spatial relations.

The trend, however, for slower response times and the finding of greater error rates in the on/off condition raise an alternative interpretation of the results: Perhaps the left hemisphere is superior at performing the more difficult task, whereas the right hemisphere is superior at performing the easier task. The importance of the differences in response times and error rates between the two tasks is difficult to evaluate, however, given the between-subjects nature of the design and the relatively small effects.

**Experiment 2**

In the previous experiment we asked subjects to make an on/off judgment in order to investigate the possibility that categorical relations are more effectively processed in the left hemisphere. Although there was good reason to select this relation, it is not the only possibility. Indeed, we must examine other cases to rule out the hypothesis that the on/off relation is special (if only by being relatively difficult to compute), and that the results are not representative of categorical spatial relations in general.

In Experiment 2 we attempted to generalize to another example of a categorical spatial relation: left/right. In this case, subjects saw a plus and a minus symbol and were asked to judge whether the plus was to the left of the minus or to judge whether the two characters were greater than an inch (2.54 cm) apart. The distances between the characters in the pairs were chosen with an eye toward making the two tasks of comparable difficulty. Exactly the same pairs of plus-minus stimuli were lateralized and evaluated in both tasks, and we again expected that the configuration in the category of the hemisphere would affect the coordination of the hemisphere.

**Method**

Subjects.

Ten students volunteered as participants, and two additional subjects were used for training.

Materials.

Each trial consisted of a single black square or circle on a white card. Each subject was seated 60 cm in front of the display, which was a cathode-ray tube. A total of 100 trials were presented to each subject, with the on/off condition included in each block of trials.

Procedure.

Subjects were instructed to respond "on" if the stimulus was correctly displayed on the card and to respond "off" if it was not. Subjects were given 2 s to respond. A feedback signal, either a tone or a visual cue, was presented 5 s after the response was made. The second trial for that condition was then presented. Each subject performed two blocks of 50 trials each, with the order of the blocks counterbalanced across subjects.

Results.

The results of Experiment 2 confirm the findings of Experiment 1. Subjects responded faster to the on/off judgment in the left hemisphere than in the right hemisphere, with a mean reaction time of 0.823 s in the left hemisphere and 0.989 s in the right hemisphere, F(1, 16) = 14.19, p < .01, MS<sub>E</sub> = 0.00338. This result is consistent with the hypothesis that categorical relations are more effectively processed in the left hemisphere.
revealed an effect of a hemispheric asymmetry on the relative time for responses to the left and right stimuli. The mean response times for the left hemisphere were significantly faster than those for the right hemisphere, with a tendency for faster responses to the left side. This asymmetry was observed in the context of a visual discrimination task.

Method

Subjects. Twenty-four right-handed Harvard University students who had not participated in Experiment 1 were tested. The stimulus display consisted of a set of 16 symbols, each presented on a card. The symbols were categorized as left, right, or center, and the task was to indicate the category of the stimulus.

Materials. The stimuli were presented on a computer screen and consisted of colored shapes (red, green, or blue) and symbols (a plus sign, a minus sign, or a circle). The stimuli were presented in a random order, and participants were instructed to respond as quickly and accurately as possible.

Results

The response times were examined using a repeated measures ANOVA. The results showed a significant effect of hemisphere on response time, with faster responses on the left side. There was also a significant interaction between hemisphere and stimulus type (left, right, or center), indicating a difference in response times for the different types of stimuli. Additionally, there was a trend for faster responses to the left than to the right, with a tendency for the center stimuli to be responded to more quickly.

Discussion

The results of Experiment 2 provide evidence for the hemispheric asymmetry in the categorization of spatial stimuli. The faster responses on the left side suggest a lateralization of function, with the left hemisphere being more involved in the task. The interaction between hemisphere and stimulus type indicates that the response times depend on the specific stimuli presented, with a trend for the center stimuli to be responded to more quickly.

Experiment 3

Experiment 3 had three main purposes. First, we wanted to generalize our previous results to another spatial relation, above/below. To examine this relation, we used a paradigm introduced by Helmholtz and Michimata (in press), which requires the participant to decide whether a stimulus is presented above or below a horizontal line. This was done in order to determine the potential for a hemispheric asymmetry in the processing of spatial relations.

Figure 3. The results of Experiment 3, which examined the above/below relation, showed a significant effect of hemisphere on response time, with faster responses on the left side. There was also a significant interaction between hemisphere and stimulus type (above, below, or center), indicating a difference in response times for the different types of stimuli. Additionally, there was a trend for faster responses to the left than to the right, with a tendency for the center stimuli to be responded to more quickly.
within 3 mm of the line. This task allowed us to examine the above/below relation as well as to easily vary the difficulty of the metric judgment.

Second, we wanted to eliminate definitively the possibility that the apparent hemisphere differences merely reflect differences in task difficulty. We hoped to reverse the trend for the categorical task to be more difficult by making the metric discrimination fairly subtle. In addition, as was done by Hellige and Michimata (in press), in this experiment we exploited the logic of reversed association developed by Dunn and Kirschner (1988) to provide strong evidence that the results do not simply reflect overall task difficulty. Dunn and Kirschner pointed out that if tasks vary in difficulty, different patterns of results from them do not necessarily imply different processing components; a single system can operate differently when under different amounts of load. In the present case, their arguments apply to the finding that the time to evaluate the stimuli depends on the task and on which hemisphere initially receives the stimuli. Because of the trend for the categorical tasks to be more difficult, this finding does not necessarily provide evidence that different processing subsystems are used in the two types of tasks.

Dunn and Kirschner (1988) proposed that a reversed association provides sufficient grounds for inferring that different processing subsystems are used in two tasks. The demonstration of a reversed association requires a minimum of three levels of one variable and is done by plotting performance on one task as a function of performance on the other task for the different levels. Dunn and Kirschner argued that if the data are plotted this way and a nonmonotonic pattern results, this is evidence that more than one process is involved. Conversely, if there was only a single underlying process, then there would be a monotonic increase in the dependent measure for both tasks over levels of the independent variable. In Experiment 3, we used three presentation conditions (presenting stimuli in the center, to the left hemisphere, or to the right hemisphere) and plotted the results for each condition against performance in the distance and above/below tasks.

Finally, Experiment 3 was designed to assess the effect of practice on task performance when stimuli are presented initially to the different hemispheres. Although changes in the performance of the hemispheres with practice have often been inferred in divided visual field experiments (see Beaumont, 1982; Bryden, 1982), rarely have clear predictions been made regarding the presence or the direction of such effects. The categorical-coordinate processing distinction provides an ideal framework in which to study such a practice effect. We hypothesize that with practice, the coordinate spatial relations encoding subsystem will be required less often for processing in the distance task. With practice, we expect new categories to develop, which will allow subjects to evaluate the close and far positions from the horizontal bar without explicitly representing metric distance. Consequently, we hypothesize that the advantage of initially presenting stimuli to the right hemisphere in the coordinate task will decrease with practice. In contrast, we do not expect any change with practice in the categorical task; if the categories are known and can be used to process the stimuli from the beginning of the experiment, there is no reason to change strategy over time.

**Method**

**Subjects.** Thirty-two right-handed Harvard University undergraduates, half of whom were men and half of whom were women volunteered to participate as paid subjects. Sixteen subjects (8 men and 8 women) participated in the task and another 16 subjects participated in the above/below task.

**Materials.** Identical stimuli were used for the categorical task and the coordinate task. They consisted of a small square dot (approximately 1 × 1 mm, or 3 × 3 pixels on the computer screen) and a horizontal line (approximately 10 mm, or 29 pixels, long and 1 mm, or 3 pixels, thick). The stimuli were presented in black on a Macintosh Plus screen with a Polaroid CP-50 filter placed over it to reduce the glare of the screen. The dot could appear in 12 different locations with respect to the line, 6 of which were above the midpoint of the line and 6 of which were below it. Three of the locations above the line were more than 3 mm away from it, and three were within 1 mm of it; this also applied to the six locations below the line. The distance between contiguous positions of the dots was approximately 0.7 mm (2 pixels).

Each of the 12 stimuli was positioned once to the right of a fixation point, once to the left of a fixation point, and once in the center of the field, which resulted in a total of 36 stimuli. In the left lateralized trials, the center of the bar was positioned at 3° of visual angle (approximately 26 mm) from the fixation point. A black exclamation mark (approximately 12 mm high and 2.5 mm thick) was presented centrally to announce the beginning of each trial. The fixation point was a black diamond approximately 2 × 2 mm (5 × 5 pixels).

The stimuli were presented at maximum luminance on the Macintosh screen (with the Polaroid filter reducing the glare). A 100 × 80 cm piece of black cardboard was placed in front of the computer with a central aperture for the screen. The cardboard served to focus the subject's attention on the screen. A voice-operated relay was used to stop the computer's timer when a response was spoken. A chin rest was used to maintain the subject's head at a constant distance from the screen. The computer was tilted slightly in order to orient the screen vertically.

**Procedure.** The categorical and coordinate tasks were conducted under identical conditions, differing only in the instructions given to the subjects. The subjects first read the instructions that appeared on the screen. Subjects were asked to make the distance judgment to decide whether the dot was less than 3 mm from the line or more than 3 mm from the line. If the dot was less than 3 mm, subjects were asked to say "in"; if the dot was more than 3 mm away from the line, subjects were asked to say "out." Subjects were asked to speak clearly into a microphone that was mounted directly in front of them at chin level. Subjects were then presented with six example of two lines that were 3 mm apart on the screen. These example consisted of a horizontal line presented twice in each of the three visual fields, once with a second, thicker horizontal line 3 mm below and once with the second line 3 mm below. Subjects asked to make the above/below judgment to decide whether the dot was above or below the line. Subjects were asked to say "up" if the dot was above the line and "down" if the dot was below the line. The subjects were then shown examples of dots plus a line, one in each field of presentation in each position. For both tasks, subjects were told to respond as quickly and accurately as possible. No practice trials were used in either task.

Each trial consisted of the following sequence: The exclamation mark appeared centrally for 400 ms; a blank field then appeared for 500 ms; a fixation point then appeared for 200 ms; and finally the stimulus appeared for 150 ms. The next trial began approximately 1.3 s after the subject's verbal response. Eight blocks of 36 trials were administered in both tasks. Trials in each block were presented in pseudorandom order with the constraint that no more than the stimuli of the same distance (more than 3 mm and less than 3 mm) did not occur in the same block. Subjects were told to monitor a cue at the beginning. The cue was given according to an alternating sequence that contained 20 times in the first block and 20 times in the second block.

**Results**

The results of the experiments were computed for each subject. Response time distributions were transformed into Gaussian time distributions.

We first analyzed the results of the previous runs. Thus, because of the large number of incorrect responses, this first analysis was computed on the incorrect time distributions. This first analysis was conducted separately on each of the three categories: the left hemispheric task, the coordinate task, and the right hemispheric task and the left hemispheric task. The results for the right hemispheric task were: $F(1, 32) = 3.15$, $p = 0.083$, $MS_e = 0.032$. (because of the large number of incorrect responses, a contrast was computed on the incorrect time distributions.)
Results

The response times were considered in ANOVAs. Prior to computing the mean response times for each condition for each subject, we removed the trials on which errors had occurred, and we eliminated outliers (which were defined as response times greater than twice the mean of the remaining times in the given cell).

We first sought to discover whether we had replicated our previous results and those of Hellige and Michimata (in press). Thus, because a practice effect was expected over trials, we analyzed separately data from the first block of both tasks. This first analysis included task (distance or above/below), presentation condition (center, left, or right), and gender as independent variables. The most interesting finding is illustrated in Figure 4, with faster mean response times for the categorical task when stimuli were presented initially to the left hemisphere and faster mean response times for the coordinate task when stimuli were presented initially to the right hemisphere. This pattern was reflected in an interaction of task and presentation condition. $F(2, 56) = 6.48, p < .003, MS_e = 0.00088.$ To clarify the nature of this interaction (because central presentations were included in the analysis), a contrast was performed to examine the specific interaction of the means for the lateralized trials. This contrast bore out our predictions, with relatively better performance indicated in the categorical relations task when stimuli were presented initially to the left hemisphere and relatively better performance in the coordinate relations task when stimuli were presented initially to the right hemisphere, $F(1, 56) = 6.90, p < .007, MS_e = 0.00098.$ Thus, we succeeded in replicating the results of Hellige and Michimata (in press). Additional contrasts were performed to examine the simple effects in the first block of trials. The subjects responded faster when stimuli were presented initially to the right hemisphere in the distance task, $F(1, 56) = 4.20, p < .01, MS_e = 0.00088,$ but did not respond faster when stimuli were presented initially to the left hemisphere in the above/below task, $F < 1, MS_e = 0.00088.$

The analysis of the response times from the first block of trials also revealed differences in the three presentation conditions, $F(2, 56) = 21.45, p < .0001, MS_e = 0.00088,$ with subjects evaluating stimuli presented in the center much faster (0.462 s) than stimuli presented initially to the left (0.508 s) or right hemisphere (0.498 s; see Figure 4). Finally, the distance judgments engendered longer response times than the above/below judgments, $F(1, 28) = 18.03, p < .0003, MS_e = 0.01881.$ Thus, this categorical task was easier than the coordinate one.

To examine further the relation between task difficulty and hemisphere effects, we plotted performance on the distance task as a function of performance on the above/below task. Mean response times for the two tasks are illustrated for each presentation condition in Figure 5. According to the reversed association criterion, the nonmonotonicity apparent in Figure 5 rules out the possibility that a single processing system is used to compute categorical and coordinate relations.

We next turned to the question of possible effects of practice. To assess such effects in detail, separate ANOVAS were performed for each task. Each analysis considered presentation condition (center, left, or right), block (one to eight), and gender.

The analysis performed on the response times from the distance task revealed that hemisphere effects did change over block, as witnessed by an interaction between block and presentation condition, $F(14, 196) = 2.01, p < .02, MS_e = 0.00086.$ To clarify the nature of this interaction, we analyzed the simple effects of block for each presentation condition. As is illustrated in Figure 6, performance changed over successive blocks when stimuli were presented initially to the left hemisphere, $F(7, 98) = 2.85, p < .01, MS_e = 0.00173,$ with a substantial decrease in response times after the first block. The corresponding analyses for stimuli that were presented initially to the right hemisphere and for stimuli that were presented in the center of the field did not show any simple effect of block ($F < 1, MS_e = 0.00173$) in each case.

The analysis of the times from the distance task also revealed that, over the eight blocks, responses were faster when stimuli were presented in the center (0.509 s) than when they were presented to the left (0.544 s) or right hemisphere (0.541 s), $F(2, 28) = 43.88, p < .0001, MS_e = 0.00106,$ for the effect of presentation condition.

In contrast to the analysis of response times from the distance task, the analysis of the response times from the

---

**Figure 4.** Results from the first block of Experiment 3, in which horizontal bar and dot stimuli were presented initially to the left hemisphere (right visual field), right hemisphere (left visual field), or both hemispheres (central field). (The subjects decided whether the dot was above or below the bar or more than 3 mm from the bar.)
above/below task provided no evidence that practice alters processing in either hemisphere. F < 1. MS_\epsilon = 0.00031, for the interaction of block and presentation condition. However, as is evident in Figure 7, central presentations again resulted in the fastest response times, F(2, 28) = 77.54, p < .0001, MS_\epsilon = 0.00039, for the effect of presentation condition. To assess possible hemisphere differences, a contrast was performed examining responses to stimuli that were presented initially to the left or right hemisphere (discarding responses to stimuli presented in the center). This analysis indicated that the above/below task was processed faster when stimuli were presented initially to the left, rather than the right, hemisphere over the eight blocks, F(1, 28) = 10.65, p < .003, MS_\epsilon = 0.00039. There was also a general decrease of response times with practice, F(7, 98) = 4.20, p < .0005, MS_\epsilon = 0.000335, as is clearly illustrated in Figure 7.

The most striking difference in Figures 6 and 7, illustrating data from the distance and above/below tasks, respectively, is between the first and second blocks of the left-hemisphere trials. There appears to be a much larger effect of practice for the distance judgments. To examine this apparent result, we performed a contrast examining whether the decrease in times when stimuli were presented initially to the left hemisphere was indeed larger for the distance task. This contrast did in fact document the different effects of practice in the two tasks, F(1, 392) = 9.23, p < .005, MS_\epsilon = 0.00056. However, in the ANOVA including all of the data, there was no difference in the effects of practice over all of the blocks in the different conditions, F(14, 392) = 1.44, p > .1, MS_\epsilon = 0.00056, for the interaction of task, presentation condition, and block. Furthermore, although times generally decreased with successive blocks, F(17, 196) = 4.41, p < .0002, MS_\epsilon = 0.00344, the overall effects of practice were the same for the two tasks, as witnessed by there being no interaction whatsoever of task and block (F < 1, MS_\epsilon = 0.00344). However, an interaction between presentation condition and block indicated that there were larger changes over block when stimuli were presented initially to the right hemisphere (collapsing over task), F(14, 392) = 1.84, p < .05, MS_\epsilon = 0.00056. In addition, the relative advantage of initially presenting stimuli to the right hemisphere in the distance task and initially presenting stimuli to the left hemisphere in the above/below task were again documented by an interaction between task and presentation condition, F(2, 56) = 4.07, p < .025, MS_\epsilon = 0.00071. This analysis also showed that even when all of the blocks were included, the distance task generally required more time than the above/below task, F(1, 28) = 20.04, p < .0002, MS_\epsilon = 0.16321, and times differed in the different presentation conditions (with the fastest times occurring with central presentation), F(2, 56) = 105.7, p < .0001, MS_\epsilon = 0.00071.

Finally, the very low percentage of errors observed in the above/below task over the eight blocks (0.35%) did not allow meaningful comparison of differences in error rates among the presentation conditions in the above/below and distance tasks. The percentage of errors was higher in the distance task, but did not differ for the presentation conditions (11.9% when stimuli were presented in the center, 10.4% when stimuli were presented initially to the left hemisphere, and 10.3% when stimuli were presented initially to the right hemisphere). Thus, there were no speed-accuracy trade-offs.

Discussion

The results from this experiment allow us to generalize to another categorical relation. We found that presenting the stimuli initially to the left or right hemisphere again had opposite effects for the two tasks, which provides further evidence that two different processing subsystems are used to compute coordinate and categorical spatial relation representations. In addition, the use of the reversed association criterion provided strong evidence of such a dissociation. Indeed, the present experiment used a task that reversed the trend in the previous experiments for the categorical task to be most difficult; the categorical task was much easier than the coordinate task in the present experiment, as was evident in both the response times and the error rates.

Figure 6. Effects of practice when subjects decided whether a dot was nearer or farther than 3 mm from a bar in Experiment 3 when stimuli were presented initially to the left hemisphere (LH), right hemisphere (RH), or both hemispheres.

Figure 7. Error rate was above central when initially presented initially to the left or right hemisphere.
This experiment not only confirms the results reported by Hellige and Michimata (in press), but also provides some insight into how categorical and coordinate visual spatial processing may change over the course of experience. We found that the advantage of initially presenting stimuli to the right hemisphere in the distance task disappeared very quickly with practice. More fine-grained analyses revealed that this effect was primarily a consequence of better performance when stimuli were presented initially to the left hemisphere, not a change in performance when stimuli were presented initially to the right hemisphere. In contrast, there was no change with practice in the advantage of initially presenting stimuli to the left hemisphere in the categorical task. These results provide support for the hypothesis that with practice the left hemisphere developed new categories that could be used at least some of the time in the distance task.

It may be worth noting that even though the apparent right-hemisphere advantage disappeared with practice in the distance task, a left-hemisphere advantage never developed. Perhaps with sufficient practice, a left-hemisphere advantage would have appeared. In any case, the fact that a left-hemisphere advantage never developed indicates that the decrease in response times over blocks of trials did not occur because the verbal responses per se became less available with practice; if the responses had become more available, we would have expected an increasing left-hemisphere advantage, given the left hemisphere's greater facility with language production (see Springer & Deutsch, 1981). Perhaps of most importance, because verbal responses were used throughout, the change over the first two blocks of the coordinate task, but not the categorical task, cannot reflect the use of verbal labels per se.

Experiment 4

The history of divided visual field experiments is somewhat checkered; it is not uncommon to find failures to replicate in the literature (e.g., see Boles, 1982; Bryden, 1976; White, 1969). Thus, we considered it prudent to replicate the results of at least one of the previous experiments. Moreover, we explored the possible role of individual differences in these failures to replicate. Kosslyn, Sokolov, and Chen (1989) reported computer simulations that suggest that there may be a wide range of ways in which high-level visual functions can be implemented in the brain. If there is in fact a large range of variation in the population, then studies with small numbers of subjects (in relation to the population) may frequently inadvertently contain heterogeneous samples. If so, then one reason studies may fail to replicate rests on differences in the samples tested, even though these studies often restrict themselves to testing only male subjects.

To explore the role of such individual differences, we tested male subjects in the distance and on/off tasks of Experiment 1 and gave them the Edinburgh Handedness Inventory (Oldfield, 1971), which is a measure of the strength of hand preference. This measure appears to be a good indicator of some aspects of laterality (cf. Annett, 1985).

Method

Subjects. Twenty-four male Harvard University students volunteered to participate as paid subjects in this experiment. No subject reported being left-handed.

Materials. The materials used in Experiment 1 were also used here. In addition, the Edinburgh Handedness Inventory (Oldfield, 1971) was used.

Procedure. The procedure was identical to that of Experiment 1, except that these subjects were tested after performing another, unrelated task (which required them to press a key whenever a dot appeared) and that the Edinburgh Handedness Inventory (Oldfield, 1971) was administered at the end of the experiment. As before, half of the subjects were assigned to the on/off group, and half were assigned to the near/far group; half of the response was counterbalanced within each group, and subjects were instructed to respond as quickly as possible while keeping errors to a minimum.

Results

The response times were analyzed as in Experiment 1, except that gender was not considered and laterality quotient (LQ; computed according to the procedure specified by Oldfield, 1971) was an independent variable; subjects in each task were divided into two groups according to a median split of the LQ scores. Higher positive LQ scores indicate a stronger right-hand preference, with 100 being the maximum (and -100 being the minimum, indicating strong left-hand preference); the mean LQ scores for the subjects who performed the on/off task were 85.6 and 45.8 for the high and low groups, respectively, and the mean LQ scores for the subjects who performed the distance task were 82.6 and 50.6 for the high and low groups, respectively.

The most important result is illustrated in Figure 8. As before, the subjects performed the on/off task relatively faster when the stimuli were presented initially to the left hemisphere and performed the distance task relatively faster when the stimuli were presented initially to the right hemisphere, $F(1, 16) = 8.68, p < .01, MS_e = 0.003337$, for the interaction of task and hemisphere. Contrasts examining the simple effects revealed an advantage when stimuli were presented initially to the right hemisphere in the distance task, $F(1, 16) = 9.72, p < .01, MS_e = 0.003337$, but no presentation differ-
ence for the on/off task. $F(1, 16) = 1.16, p > .1, MS_1 = 0.003337$. This interaction, in turn, depended on the LQ scores, $F(1, 16) = 5.77, p < .05, MS_1 = 0.003337$, for the interaction of task, hemisphere, and LQ. As is illustrated in Figure 8, only the more strongly right-handed subjects showed differences in task performance when stimuli were presented initially to the different hemispheres. Indeed, for the high-LQ group, contrasts revealed an advantage of initially presenting stimuli to the left hemisphere in the on/off task, $F(1, 16) = 5.26, p < .05, MS_1 = 0.003337$, and an advantage of initially presenting stimuli to the right hemisphere in the distance task, $F(1, 16) = 9.35, p < .01, MS_1 = 0.003337$; in contrast, neither effect was significant for the low-LQ group, $F < 1$ and $F(1, 16) = 1.76, p > .1, MS_1 = 0.003337$, for the on/off and distance tasks, respectively. It is also noteworthy that there was no hint of an overall difference in time for the two tasks, $F < 1, MS_1 = 0.0928$, and that, if anything, the distance task now required more time than the on/off task.

The error rates were also analyzed. The most important findings here exactly mirror those from the response times: More errors occurred when stimuli in the on/off task were presented initially to the right hemisphere, and slightly more errors occurred when stimuli in the distance task were presented initially to the left hemisphere. $F(1, 16) = 5.73, p < .05, MS_1 = 0.65625$, for the interaction of task and hemisphere. As before, this pattern of results was only evident for the strongly right-handed subjects, $F(1, 16) = 7.00, p < .02, MS_1 = 0.65625$, for the interaction of task, hemisphere, and LQ. However, the less strongly right-handed subjects committed more errors in general when stimuli were presented initially to the right hemisphere, and they also responded more quickly in this condition. This unfortunate speed-accuracy trade-off prevents us from saying much about this particular result. There was also an interaction between hemisphere, response, and hand assignment for responses, $F(1, 16) = 8.67, p < .01, MS_1 = 0.6334$, which seemed to indicate that the contralateral hand responded more accurately, especially for near and on responses.

Finally, we again analyzed separately only the data from the stimuli that were used in both conditions of the experiment. As in Experiment 1, there was a relative advantage of initially presenting the stimuli in the on/off task to the left hemisphere, and there was a relative advantage of initially presenting the stimuli in the distance task to the right hemisphere, $F(1, 16) = 8.94, p < .01, MS_1 = 0.00487$, for the interaction between task and hemisphere (with means of 0.755 and 0.787 s for the on/off task and of 0.851 and 0.797 s for the distance task, when stimuli were presented initially to the left and right hemispheres, respectively). Contrasts examining the simple effects revealed an advantage of initially presenting stimuli to the right hemisphere in the distance task, $F(1, 16) = 7.01, p < .01, MS_1 = 0.00487$, but no presentation effect for the on/off task, $F(1, 16) = 2.50, p > .1, MS_1 = 0.00487$. The interaction between task and hemisphere reflected data primarily from the strongly right-handed subjects, as was evident in an interaction of task, hemisphere, and LQ, $F(1, 16) = 5.43, p < .05, MS_1 = 0.00487$. (For the strongly right-handed subjects, the means were 0.781 and 0.846 s for the on/off task and 0.925 and 0.837 s for the distance task, when stimuli were presented initially to the left and right hemispheres, respectively; for the less strongly right-handed subjects, the corresponding means were 0.729 and 0.729 s for the on/off task and 0.777 and 0.758 s for the distance task. The contrasts examining the simple effects for the high-LQ group revealed that subjects evaluated stimuli faster when they were presented initially to the left hemisphere in the on/off task, $F(1, 16) = 5.05, p < .05, MS_1 = 0.00487$, and faster when they were presented initially to the right hemisphere in the distance task, $F(1, 16) = 9.45, p < .01, MS_1 = 0.00487$; in contrast, neither difference was significant for the low-LQ group ($F < 1, MS_1 = 0.00487$) in both cases. Finally, the dearth of errors for these trials prevented meaningful analysis of the error rates.

**Discussion**

The results of this experiment replicated those from Experiment 1. We again found a relative advantage of presenting stimuli initially to the left hemisphere in the on/off task, and a relative advantage of presenting stimuli initially to the right hemisphere in the distance task. However, even though the pattern of results statistically generalized over all of the subjects, there was evidence that this pattern reflected primarily data from strongly right-handed subjects. This finding is of interest for two reasons. First, it supports our inference that the response times reflect differences in the processing of the cerebral hemispheres and not scanning effects or the like (see Beaumont, 1982). Second, Kosslyn et al. (1989) posited that categorical encoding would tend to be lateralized along with speech production; if measures of handedness are correlated with such lateralization (at least in people who are primarily right-handed, as is supported by data reviewed in Annett, 1985), then the present result is consistent with this expectation. However, the generally higher errors when stimuli were presented initially to the right-hand side may indicate that we have not yet mastered the task difficult task...
presented to the right hemispheres of the less strongly right-handed subjects is a source of some concern, making it difficult to interpret this finding.

General Discussion

We began these investigations by considering possible ways in which certain capabilities of our visual systems might arise. Specifically, we hypothesized that one type of representation of spatial relations would be useful for recognizing semirigid objects, whereas another would be useful for recognizing or encoding subtle differences in location. In the former case, we hypothesized that categorical spatial relation representations could be used to preserve what is common across the different shapes of semirigid objects, whereas in the latter case we hypothesized that coordinate spatial relation representations could be used to specify precise positions. The present experiments provide evidence for the psychological and neurological reality of the distinction between the two kinds of representations. We consistently found that when stimuli were presented initially to the left hemisphere, categorical spatial relations could be encoded and evaluated relatively more quickly; in contrast, when stimuli were presented initially to the right hemisphere, coordinate spatial relations could be encoded and evaluated relatively more quickly (provided that subjects had not practiced the task too much, as will be discussed shortly). This was true when subjects were asked to evaluate the categorical relations on/off, left/right, and above/below and when they were asked to evaluate distances relative to 2 mm, 3 mm, and 1 in. (2.54 cm) (and whether they responded manually or orally). We showed that this result is not due to differences in the difficulty of performing the different judgments.

Our data by necessity reflect processing. Thus, one could wonder whether we have evidence for a difference in representation or only for a difference in processing. That is, one might argue that the same representation is used in both tasks but that processing is different in the two cases. However, recent work on parallel distributed processing calls into question whether one can make a sharp distinction between representation and process; structure and process are thoroughly entwined within a parallel distributed-processing network (see Rumelhart & McClelland, 1986). In this light, it may be best to focus on properties of representational systems, which include representations and processes working together. In these terms, the present results provide evidence for two subsystems that are used to represent spatial information, one of which is specialized for encoding categorical spatial relations and one of which is specialized for encoding coordinate spatial relations. Because the subsystems are differentiated on the basis of the kind of information they encode, it is appropriate to characterize them as computing different representations.

The present results are consistent with many findings reported in the neuropsychological literature. For example, Umlitl et al. (1974) found that normal subjects encode easily categorized line orientations (vertical, horizontal, and 45° diagonal) better when they are presented initially to the left hemisphere, and encode difficult-to-categorize oblique lines better when they are presented initially to the right hemisphere. Similarly, there is much evidence in the clinical literature that is consistent with our distinction between categorical and coordinate spatial relations encoding. Taylor and Warrington (1973), Warrington and Rabin (1970), and Hannay, Varney, and Benton (1976) all reported that right-hemisphere damage disrupts a patient's ability to localize a dot more than left-hemisphere damage does. However, Ratcliff and Davies-Jones (1972) failed to find such an effect, which was subsequently attributed by Hannay et al. to the task's being too easy; Hannay et al. did obtain a deficit for patients with right-hemisphere damage when they performed a more difficult version of the task.

We also found that the advantage of initially presenting stimuli to the right hemisphere in the distance task disappeared rather quickly with practice in Experiment 3. One possible account for this practice effect is that subjects simply learned verbal labels. However, the subjects must have had verbal labels to begin with, or they could not have understood the instructions and produced the appropriate responses. Verbal labels were used in both tasks, and hence this factor cannot account for differences between them. The left hemisphere's difficulty in performing the distance task apparently was in forming the perceptual category that is subsumed by the label. Indeed, formation of the perceptual category logically must be prior to verbal labeling: without the category, the label cannot be applied. (Even when metric judgments are made, at some point in processing a category must be formed if a label is to be applied, albeit a very narrow and specific category that is based on an approximation to an analog measurement.) Furthermore, the notion that verbal mediation may lie at the heart of categorical processing is also belied by the fact that we often found weak left-hemisphere superiority in the categorical tasks (as revealed by contrasts examining the simple effects); the left hemisphere is clearly superior at linguistic processing and should consistently have been better at such judgments if verbal mediation was used. (Note, however, that the simple fact of an interaction between task and hemisphere is all that is needed to support the psychological and neurological distinction between the two kinds of processing subsystems, provided that a reversed association occurs; cf. Hellige, 1983.)

Thus, the practice effect between the first two blocks of trials observed in Experiment 3 suggests that new categorical spatial relation representations can be developed as needed. However, if this is true, why was there not a continuing interaction over blocks of trials, leading to a strong left-hemisphere advantage by the eighth block? In subsequent work, Koenig, Gabrieli, Kosslin, Lin, and Chabris (1989) found that when subjects are brought back for a second testing session on the next day, the original right-hemisphere advantage in the distance task is again present at the outset. Apparently, the category can be set up initially fairly quickly but takes a relatively long time to consolidate. In connectionist terms, "fast weights" might be used to form the initial representation (see Rumelhart & McClelland, 1986), but a slower process is needed to adjust the permanent weights in a network for actual learning. If so, the fast-weight categories apparently are not as efficient as the consolidated represen-
tations, which apparently take relatively large amounts of practice to induce.

Our finding that categorical spatial relation representations can be developed as needed leads to an important cautionary note concerning the conflicting findings on dot localization with normal subjects. Although Kimura (1969) found in several experiments that normal subjects localized dots better when they were presented initially to the right hemisphere, her findings have not always been replicated by others (e.g., see Bryden, 1976). It is important to realize that a given task or stimulus type does not guarantee that a specific type of presentation will be used. In this case, it is possible that subjects could accomplish this task using either categorical or coordinate spatial relations. For example, once they are aware of the precision necessary for the response, subjects could use categorical relations to describe dot position in terms of nested quadrants (by dividing the field into quarters and each quarter into quarters, etc., as needed); in this case, a fairly concise description, such as upper left, lower right, upper right, could in principle be used to specify spatial location. Seemingly minor variations in the instructions, stimuli, shape of the screen, or amount or type of practice could engender different strategies.

Thus, it is probably an error to conceive of categorical spatial relations as a static property of our mental repertoire. At first glance, the argument that such representations are somewhat dynamic, changing over time, may seem obvious, if only because the relation left/right is not mastered until 7 years of age or later by most people. However, this observation does not imply that categorical spatial relations are always learned; they could rely on neural substrata that are not developed until specific ages. Hence, it is of real interest that the results from Experiment 3 suggest that at least some form of categorical spatial representation develops with practice. At this juncture we cannot say what the range of possible categorical spatial relations is, but this is a critical question. For example, can one inch to the left become a categorical relation? If so, it will be impossible to decide in principle what spatial relation will be stored using a categorical or coordinate representation; this will become an empirical question, with the answer possibly varying from individual to individual, from profession to profession, from culture to culture, and from task to task.

Categorical representations of spatial relations are particularly interesting when viewed from a broader perspective. Many theorists have speculated that the semantics of language are rooted in perception (e.g., Anderson & Bower, 1973; Clark & Clark, 1977; Lakoff, 1987). Any semantic representation must be categorical and must have the proper combinatorial properties. These characteristics are part and parcel of categorical spatial relations; by definition, they are categorical and have combinatorial properties (because they serve to relate two or more entities). Hence, it is possible that these sorts of representations may play a fundamental role in language processing. If so, it would not be an accident that the left cerebral hemisphere is apparently more efficient at using them. Thus, to the extent that we come to understand the nature of categorical spatial relations, and other kinds of categorical perceptual representations, we may be providing the foundations for theories of many aspects of cognitive processing.

We must also add another cautionary note: Experiments 1, 2, and 4 were completed in 1986, and some aspects of the results were briefly summarized in Kosslyn (1987). Publication was delayed because our tachistoscope died after Experiment 4, and we subsequently failed to obtain the results of Experiment 2 in a variation using an Apple II computer for presentation. Four subsequent efforts using the Apple II produced mixed results. This disturbing turn of events resulted in a series of methodological considerations in which we attempted to discover why the results were erratic. The results of Experiment 2 proved reliable when subjects were presented using back-projected slides, and the results of Experiment 3 were replicated using the higher resolution Macintosh screen with a contrast-enhancing Polaroïd filter. Although we did not succeed in determining precisely which difference was critical, the results are reliable when high-resolution, low-glare, black-on-white stimuli are used. We can offer no compelling account of why these variables are important (see also Sergent & Hellige, 1986).

References


Received August 1, 1988
Revision received December 24, 1988
Accepted December 29, 1988