Categorical and Metric Spatial Processes Distinguished by Task Demands and Practice

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Abstract

■ In this study we examined Kosslyn's (1987) claim that the right hemisphere exhibits a relative superiority for processing metric spatial relations, whereas the left hemisphere exhibits a relative superiority for processing categorical spatial relations. In particular, we examined whether some failures to observe strong visual field (VF) advantages in previous studies might be due to practice effects that allowed individuals to process tasks in alternative manners (e.g., to process a metric task using a categorical strategy). We used two versions of a task previously employed by Hellige and Michimata (1989) in which individuals judge the metric (distance) or categorical (above/below) spatial relations between a bar and a dot. In one version, the position of the bar was held static. In another, the bar's position varied. This manipulation prevented participants from using the computer screen as a reference frame, forcing them to compute the spatial relationships on the basis of the relevant items only (i.e., the bar and the dot). In the latter, but not the former version of the task we obtained evidence supporting Kosslyn's hypothesis, namely, a significant right visual field (RVF) advantage for categorical spatial processing and a trend toward a left visual field (LVF) advantage for metric spatial processing. Furthermore, the pattern of results for trials on which information was presented centrally (CVF trials) was similar to that observed on RVF trials, whereas the pattern for trials in which identical information was presented in each visual field (BVF trials) was similar to that observed on LVF trials. Such a pattern is consistent with Kosslyn's suggestion that categorical processing is better suited for cells with small receptive fields and metric processing for cells with larger receptive fields. ■

INTRODUCTION

Kosslyn and his colleagues have proposed that there are two independent modes of processing spatial relationships, categorical and metric (sometimes referred to as coordinate), that rely on distinct neural substrates. As conceptualized by these researchers, categorical spatial relations are those in which the spatial relationship between items can be described by discrete, nonoverlapping categories (e.g., above and below) and are thought to be performed with relative superiority by left-hemisphere processing mechanisms. In contrast, metric spatial relationships are those computed along a continuum, such as required in distance judgments (e.g., 1 versus 2 in.), and are performed with relative superiority by right-hemisphere processing mechanisms. Furthermore, these two types of spatial processing are posited to be orthogonal because characterizing the spatial relationship between two items via one means (e.g., categorically) provides no information about the relationship between the items via the other (e.g., metrically) (Kosslyn, 1987; Kosslyn et al., 1989). For example, describing the relationship between a cup and a tea kettle in categorical terms, such as stating that the cup is to the left of the tea kettle, provides no information about their metric relationship—that is whether the cup is 1 in., 6 in., 1 ft, or 3 ft away from the tea kettle.

Kosslyn has put forth a number of possible and not mutually exclusive mechanisms by which these hemispheric differences in spatial processing might arise. First, he (Kosslyn, 1987) suggested that the left hemisphere's facility for categorical spatial relations might have arisen because language, for which the left hemisphere is specialized, hinges on the formation of categories. Thus, the left hemisphere might be adept at all sorts of categorization, even spatial categorization. In contrast, he posited that the right hemisphere is adept at metric spatial relations because computing such relations is essential for navigation, which he argues is a task for which the right hemisphere is specialized (it is most likely the case that the right hemisphere is skilled at some forms of navigation but not all; see Banich, 1997, chapter 6 for a further discussion of this issue).

Secondly, Kosslyn, Chabris, Marsolek, and Koenig (1992) have suggested that hemispheric differences in processing spatial relations might derive from hemispheric differences in the processing of lower-level visual information. They suggest that categorical decisions may be made more rapidly by a system with small, nonoverlapping receptive fields, whereas a system with larger, overlapping receptive fields may be more efficient at making metric decisions. They provide converging evidence for such an assertion with computational modeling (although see Cook, Früh, & Landis, 1995, for a critique of this approach, and Kosslyn, Chabris, Marsolek, Jacobs, & Koenig, 1995, for a reply). Such an approach is compatible with much work by Sergent, who has suggested that hemispheric differences in the processing of sensory information can influence or underlie hemispheric differences in higher cognitive processes (e.g., Sergent, 1985). It is also consistent with findings of differential hemispheric sensitivity to different channels or bands of low-level sensory information. For example, it has been reported that the left hemisphere is biased to process information containing relatively higher spatial frequencies in the visual modality (Christman, Kitterle, & Hellige, 1991) as well as information of relatively higher auditory frequency (Ivry & Lebby, 1993). In contrast, the right hemisphere is biased to process information of a relatively lower spatial, or auditory, frequency. Hemispheric differences in sensitivity to other low-level visual parameters such as luminance, contrast, and exposure duration have also been reported (e.g., Christman, 1989).

Most recently, Kosslyn has suggested that differences in attentional biases between the hemispheres may also contribute to differences in spatial processing (Kosslyn, Anderson, Hillger, & Hamilton, 1994; Chabris & Kosslyn, 1998). This view maintains that for many tasks it is not possible to attend to both large and small regions of space at the same time (e.g., focusing on grasping the handle of a mug precludes a perception of the entire mug). Thus, there is a need for two separate types of attentional biases, one for small regions of space and one for large regions. The left hemisphere is viewed as having an attentional bias toward processing information from small regions of space—a bias induced in part by a tendency toward monitoring information from neurons with relatively small, nonoverlapping receptive fields, which provide relatively high resolution output. In contrast, the right hemisphere is viewed as biased toward devoting attention to larger regions of space because it tends to monitor information from neurons with relatively large and overlapping receptive fields. Moreover, these attentional biases are viewed as being sensitive and adjustable to task demands, with the left hemisphere better able to adjust the scope of attention than the right.

Evidence that such attentional processes play a role in spatial processing was provided by Kosslyn et al. (1994). In their study, participants were asked to make judgments about the relative distances between two lines that varied in their retinal eccentricity. If hard-wired differences in receptive field sizes are driving the system, shifting the stimuli more into the periphery should increase the right-hemisphere advantage for all types of judgments, as receptive field size increases with increasing retinal eccentricity. Contrary to this prediction, they did not observe such a shift but rather found that the left-hemisphere advantage for items closer together (i.e., within a small span of spatial attention) remained across all eccentricities.

Regardless of the mechanism involved, Kosslyn's theory predicts that categorical judgments should be made more quickly and accurately when information is presented in the right visual field, or RVF (which initially projects to the left hemisphere), whereas metric judgments should be made more quickly and accurately when information is presented in the left visual field, or LVF. Numerous empirical studies have examined these claims (Cowin & Hellige, 1992; Hellige & Michimata, 1989; Hellige et al., 1994; Hoyer & Rybash, 1992; Koenig, Reiss & Kosslyn, 1990; Kosslyn et al., 1989; Laeng, 1994; Laeng & Peters, 1995; Rybash & Hoyer, 1992; Sergent, 1991a, 1991b; Servos & Peters, 1990). In one of the first tests of this hypothesis, Hellige and Michimata (1989) used a paradigm in which neurologically intact individuals were shown a bar along with a dot. On a given trial, the dot was situated in one of 12 positions relative to the bar (6 above and 6 below). In the categorical version of the task, individuals judged whether the dot was above or below the bar, regardless of how far displaced the dot was from the bar. In the metric task, individuals decided whether the dot was near to the bar or far from it, with participants being shown visually that near was considered within 2 cm of the bar (far being more distant). They obtained a significant interaction between task (categorical, metric) and visual field (LVF, RVF), which they subsequently replicated (Hellige et al., 1994). In particular, for the categorical task they obtained a marginally significant reaction time (RT) advantage for RVF trials, and for the metric task, a significant LVF advantage.

Although some subsequent reports provide results consistent with Kosslyn's theory, others do not. A study by Laeng (1994) with patients who had sustained unilateral brain damage provides corroborative evidence. In this study, patients were presented with a picture to view for 5 seconds. Five seconds later they were shown both the original picture and a variant of that picture, with their task being to decide which of the two was identical to the one viewed earlier. In half of the trials, the variant contained changes in the categorical spatial relationships relative to the original (e.g., in the original picture the small cat was to the left of the large one, whereas in the variant the small cat was now to the right of the large one). In the other half, the metric relationship was changed (e.g., the distance between the cats was increased in the variant relative to the original although the relative positions of the cats remained the same). Laeng found that when the patients made an error (i.e., chose the variant rather than the original), it varied depending on which hemisphere was damaged. Patients with left-hemisphere lesions were more likely to pick the variant in which the categorical, rather than the metric, relation had been changed—suggesting that these patients were insensitive to deviations in categorical relations. Patients with right-hemisphere lesions did the opposite—when they made errors, they were more likely to choose the variant in which the metric relationship had been altered.

The results of studies with neurologically intact individuals have been a bit more equivocal. Hemispheric differences in preferential modes of processing spatial relations as suggested by Kosslyn have indeed been observed in neurologically intact individuals by other researchers (e.g., Hellige & Michimata, 1989; Hellige et al., 1994; Kosslyn et al., 1989; Laeng & Peters, 1995; Servos & Peters, 1990). However, some results are only partially consistent with Kosslyn's theory. For example, Sergent (1991a) only obtained results compatible with Kosslyn's theory in one out of four studies (Experiment 4) and did not obtain a RVF advantage for categorical processing. Although Hellige and colleagues (Hellige & Michimata, 1989; Hellige et al., 1994) do obtain a significant interaction between VF and task, they do not always obtain a significant VF advantage for each task. Furthermore, there are a number of reports that, even when visual field advantages are present, they tend to attenuate with practice. For example, in a study with children, Koenig et al. (1990) found that a significant interaction between visual field and task was limited to the first block of trials. Likewise, Kosslyn et al. (1989) found that the right-hemisphere advantage on the metric task dissipated with practice. They suggested that with time individuals learn to transform the metric judgments into categorical ones by forming categories for stimulus configurations.

In an attempt to address the degree to which practice effects can modify asymmetries for metric and categorical aspects of spatial processing, Rybash and Hoyer (1992) created another version of the bar and dot task in which individuals saw two square dots and a line. For the categorical task, the decision remained quite similar (Are the dots above or below the line?). In the metric task, individuals judged whether the bar would fit between two square dots, a task Rybash and Hoyer believed would be more resistant to categorization. They then examined the visual field asymmetry for both the original and modified version of the dot and bar tasks across blocks. A RVF advantage was not obtained across any of the blocks for either the original or modified version of the categorical task. Even though the modified version of the coordinate task was harder than the original, both yielded a LVF advantage in the first of three 36-trial blocks that dissipated over the remaining two blocks because of improvement on RVF trials. A study with older adults revealed a similar pattern of performance (Hoyer & Rybash, 1992).

Cowin and Hellige (1994) using the original bar and dot stimuli (i.e., those used by Hellige and Michimata, 1989) also found a LVF advantage (in accuracy) for metric spatial relations that disappeared after the first of four 24-trial blocks because of improvement in performance on RVF trials. This pattern was not influenced by whether the stimuli had been subjected to dioptric blurring, a process designed to disrupt the extraction of information of high spatial frequency. Such a finding suggests that the mechanism that generates improved performance on RVF trials is not better extraction of information of high spatial frequency. Rather, the Cowin and Hellige data suggest that the improvement in left-hemisphere performance that causes a shift away from a LVF advantage is more likely to be mediated by a higher-level cognitive strategy than by a lower-level perceptual mechanism.

In considering the inconsistency of previous findings, we were interested in pursing the degree to which higher-level cognitive strategies might influence the processing of spatial information. We were especially interested in considering those strategies that might enable a metric task to become processed, with practice, in a categorical manner. We hypothesized that in previously employed versions of the Hellige and Michimata (1989) task, the computer screen itself may become a reference frame that can preclude the need to calculate relations between the items on which the judgment should be based. For example, in the coordinate (near/far) task previously used in many studies, the participant may learn to draw two imaginary lines on the computer screen that will segment the screen into regions that can easily be named as near the bar or far from the bar (see Figure 1a). The near/far task can then be performed not by examining the distance between the bar and the dot (i.e., by making a metric calculation) but by just simply deciding whether the dot falls within the "near" or "far" regions of the screen. In fact, Kosslyn et al. (1992) have suggested that the left hemisphere divides the regions surrounding the important object into "bins" that have a specific spatial relation to the object being attended. As long as a second object falls within one of these bins, its relationship to the main object can be easily categorized. Employing such a strategy for the near/far task could explain the shift toward left-hemisphere processing. Likewise, the relationship between the bar and the dot may not need to be considered for correct performance on the categorical (above/below) task, either. Rather, by drawing an imaginary line across the middle of the screen, the participant may just decide if the dot is positioned in the top or bottom half of the screen (Figure 1b).

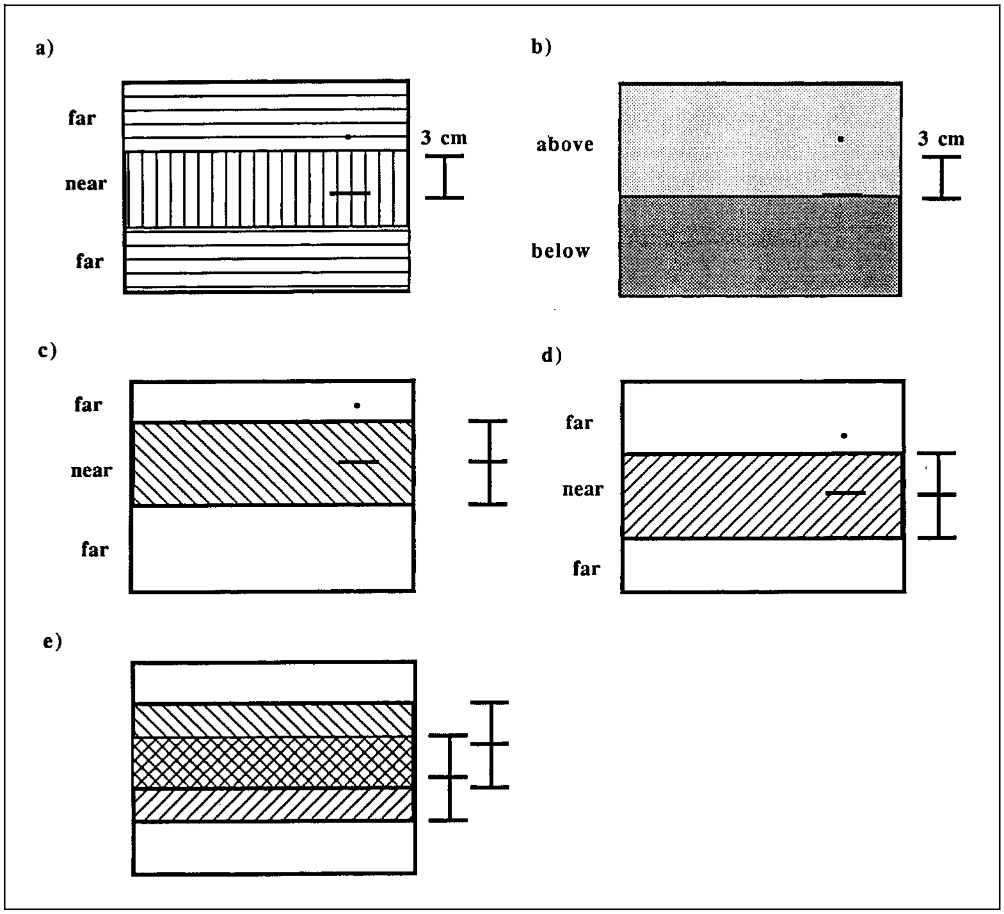

Figure 1. The way in which the computer screen can act as a frame of reference when the bar's position is static. When the bar's position is static, individuals needn't examine the relative positions of the bar and dot to reach a correct decision because regions of space on the computer screen can be used to do so as illustrated here (a) for metric tasks and (b) for categorical tasks. However, when the bar's position varies from trial to trial, such a strategy will not work. For example, when the bar is in the upper position, the shaded area represents the near region as shown in (c) and when the bar is in the middle position, the near region (shaded) is now different as shown in (d). Thus, as illustrated in (e) there is now no unique region of the screen that is associated with a near response and one that is associated with a far response.

To discourage participants from using such a strategy, one would like to utilize a task that (1) requires the relationship between the bar and the dot to be computed on each trial and (2) precludes the reference frame of the computer from providing redundant information about the correct answer. To do so, we borrowed an approach from the computational modeling of Kosslyn et al. (1992), which was to vary the position of the bar from trial to trial. By varying the position of the bar, we can ensure that judgments about the relationship between the bar and the dot are made on the basis of these two items and cannot be based on the regions of the computer screen in which the dot appears (see Figures 1c to e for an example of how this manipulation will affect metric processing). Unlike the Kosslyn et al. simulation in which the bar could appear in any of five locations, we designed trials in which the bar could appear at one of three vertical locations. We contrasted performance on this version of the task (the "variable" condition) with a version in which the position of the bar remained constant (the "static" condition), which is essentially identical to the method used by Hellige and colleagues (Hellige & Michimata, 1989; Hellige et al., 1994) and Kosslyn et al. (1989, Experiment 3), and similar to that of Sergent (1991a, Experiment 2). Furthermore, we examined visual field asymmetries for the two versions of this task over four blocks of trials. This approach allowed us to determine whether VF asymmetries would be more resilient to practice effects in the variable bar condition than in the static bar condition, because the variable bar condition would make it difficult to employ alternative strategies.

Another objective of the present study was to examine how spatial processing by each hemisphere compares to that which occurs when both hemispheres receive information. We examined two different conditions that allow both hemispheres to have access to information—one condition in which the same information is presented laterally to each hemisphere (bilateral visual field, BVF) and another in which information is presented in central vision (central visual field, CVF). Hellige and Michimata (1989) found that the pattern of performance on BVF trials was more similar to that observed on RVF trials than on LVF trials. For both RVF and BVF trials, the difference in RT between the above/below categorical task as compared to the near/far metric task was greater than for LVF trials (a result also obtained by Hellige et al., 1994). Kosslyn et al. (1989; Experiment 3) and Rybash and Hoyer (1992) employed a CVF condition, but neither of these studies explicitly contrasted the pattern of performance on such trials with those in the LVF and RVF. However, the figure depicting the results of Kosslyn et al. (Figure 4) suggests that processing on CVF trials looks more like that observed on RVF than LVF trials. Sergent (1991a; Experiment 2) included both CVF and BVF trials and found that responses to CVF trials were faster than to RVF, LVF, and BVF trials but did not obtain a visual field by task interaction. Kosslyn et al. (1989) also found faster responses on CVF trials than unilateral trials, consistent with Sergent.

In our study, we have included both CVF and BVF trials because we believe that Kosslyn's theory allows specific predictions as to how these trials should be processed. If, as Kosslyn et al. (1992) have suggested, the size of the receptive field most suited for categorical processing is smaller than that for metric processing, we might predict that the ability to process spatial information in a categorical manner relative to a metric manner should be more pronounced for CVF than BVF trials. Such a prediction derives from the fact that information presented centrally will be foveated and fall in an area of sensory receptors with smaller receptive fields. Because the studies of Kosslyn (Kosslyn et al., 1989, Experiment 3), Hellige and colleagues (Hellige & Michimata, 1989; Hellige et al., 1994), and Rybash and Hoyer (1992; Hoyer & Rybash, 1992) do not allow the examination of such predictions, and Sergent (1991a, Experiment 2) didn't explicitly address this issue, we wished to do so in our study.

A final purpose of our study was to examine how individual differences in asymmetric hemispheric activation would affect performance on this task. Levy, Heller, Banich, and Burton (1983a) have suggested that individuals have a characteristic bias to engage the processing mechanisms of one hemisphere over that of the other, regardless of task demands. Supporting this suggestion are findings of a positive association between an individual's perceptual asymmetry scores across tasks (Kim & Levine, 1991; Levine, Banich, & Koch-Weser, 1984, 1988; Levine, Banich, & Kim, 1987). It has been found that individuals who are right-hemisphere biased exhibit a larger than average LVF advantage on right-hemisphere tasks and a smaller than average RVF advantage on left-hemisphere tasks. In both cases the individual's score is biased toward right-hemisphere processing relative to the group mean. Likewise, an individual who is left-hemisphere biased will exhibit a larger than average RVF advantage on left-hemisphere tasks and a smaller than average LVF advantage on right-hemisphere tasks.

This characteristic asymmetric hemispheric activation has been found to account for a significant amount of the variance (45 to 50%) in perceptual asymmetry scores across tachistoscopic tasks (Kim & Levine, 1992; Kim, Levine & Kertesz, 1990) and to predict the level of performance on free vision tasks that are thought to rely substantially on the processing capacities of one hemisphere (i.e., reading comprehension—left hemisphere; face recognition—right hemisphere) (Banich, Elledge, & Stolar, 1992). Recently, however, other researchers have failed to obtain evidence for individual differences in asymmetric hemispheric activation because positive correlations among asymmetry scores across a wide variety of tasks are not always observed (e.g., Boles, 1992; Hellige et al., 1994). In particular, Hellige et al. (1994) found no relationship between performance on the spatial task employed by Hellige and Michimata (1989) and the chimeric face test (Levy, Heller, Banich, & Burton, 1983b) that has often been used to classify individuals with regard to asymmetric hemispheric activation (e.g., Banich, Elledge, & Stolar, 1992). This null result is worth reexamining for a number of reasons. First, in the Hellige et al., study no correlation was found between the chimeric face test and a CVC task, although such an association has been observed previously by Hellige himself (Hellige, Block, & Taylor, 1988) and also by Levy et al. (1983a) and Belger (1993). Given that this relationship between the lateralized CVC task and the chimeric face task is relatively robust, but was not obtained by Hellige et al., it is possible that the lack of correlation with the spatial task may also be an atypical result. Furthermore, Belger and Banich (1998) have recently found that the asymmetric hemispheric activation of an individual can predict the degree to which integration of information across the hemispheres is advantageous to task performance. Thus, it might be that even if asymmetric hemispheric activation, as measured by the chimeric face test, does not predict performance on RVF or LVF trials, it would do so for trials in which both hemispheres have access to information, namely, BVF and CVF trials.

RESULTS

Because our investigation had two distinct focuses, those related to hemispheric specialization and those related to interhemispheric interaction, we examined the relevant trials separately. LVF and RVF trials (lateral trials) were examined to investigate effects of hemispheric specialization, whereas CVF and BVF trials (bihemispheric trials) were analyzed to examine the effects of interhemispheric interaction.

Only those trials on which the individual responded correctly were included in the analyses of reaction time. Furthermore, the reaction time data were trimmed so that responses two standard deviations above or below the mean for an individual subject were excluded. This procedure resulted in a very small number of responses being excluded.

Lateral Trials

Reaction Times

A repeated-measures analysis of variance (ANOVA) with the between-subjects factor of Hemispheric Bias (right hemisphere, left hemisphere), and the within-subjects factors of Decision (categorical, metric), Bar Position (static, variable), Block (1,2,3,4), and VF (RVF, LVF) was performed on mean RT. There were main effects of

Decision ($F(1,30) = 27.11, p < 0.0001$), Bar Position ($F(1, 30) = 14.34, p < 0.001$) and Block ($F(3, 90) = 4.74, p < 0.005$). Categorical decisions (344 msec) were made more quickly than metric decisions (403 msec); decisions were made more quickly when the bar's position was static (362 msec) rather than variable (386 msec); and responses in block 4 (359 msec) were significantly faster than in block 1 (385 msec) (Newman-Keuls pairwise comparisons, $p < 0.05$).

The Decision by Block interaction was significant ($F(3, 90) = 3.12, p < 0.05$) because speed of response for the categorical task decreased most between blocks 1 and 2, whereas it decreased most between blocks 3 and 4 for the metric task. This interaction was modified by a significant Decision by Block by VF interaction ($F(3, 90) = 6.92, p < 0.001$), which in turn was moderated by a significant Bar Position by Decision by Block by VF interaction ($F(3, 90) = 5.76, p < 0.005$). The Decision by Block by VF interaction occurred because there was only a marginally significant difference between the pattern on categorical and metric trials for each VF for blocks 1 and 2 ($F(1,30) = 3.93, p < 0.057$) but a highly significant interaction for blocks 3 and 4 ($F(1, 30) = 11.84, p < 0.0025$). For these last two blocks, performance on RVF trials (block 3: 329 msec; block 4: 327 msec) was significantly faster than on LVF trials (block 3: 344 msec; block 4: 346 msec) for the categorical task ($F(1, 30) = 9.07, p < 0.01$), with nonsignificantly better performance on LVF than RVF trials for the metric task ($F(1, 30) = 1.60, p = 0.22$) (LVF, block 3: 410 msec; block 4: 377 msec; RVF, block 3: 419 msec; block 4: 385 msec). The four-way interaction indicated that the pattern in the three-way interaction was due entirely to the condition in which the bar's position was variable ($F(1, 30) = 22.90, p < 0.0001$) but not when it was static ($F(1, 30) = 0.281, p = 0.60$) (see Figures 2 and 3).

The only effect involving the grouping factor of Hemispheric Bias was an interaction with Bar Position and VF ($F(3, 90) = 6.92, p < 0.05$). This interaction resulted because the pattern for the RH and LH groups was significantly different. For the RH group, the advantage in responding when the bar's position was static was greater for LVF (25 msec; 362 versus 387 msec) than for the RVF trials (14 msec; 363 versus 377 msec), although not significantly so ($F(1, 30) = 2.20, p = 0.149$). In contrast, for the LH group, this advantage was almost significantly greater for RVF (35 msec; 357 versus 392 msec) than for LVF trials (23 msec; 365 versus 388 msec) ($F(1, 30) = 3.66, p = 0.065$). Thus, the manipulation of the bar's position had more of an effect in the VF opposite an individual's more activated hemisphere.

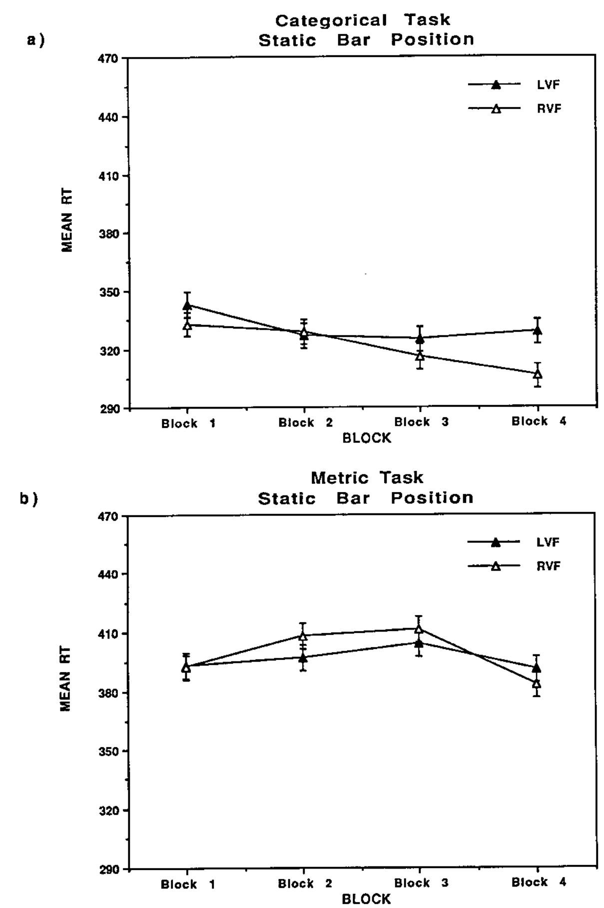

Figure 2. Performance as measured by mean RT from stimulus offset on the (a) categorical task and (b) metric task for LVF & RVF trials when the bar's position was static.

Error Rates

A repeated-measures ANOVA with the between-subjects factor of Hemispheric Bias (right hemisphere, left hemisphere) and the within-subjects factors of Decision (categorical, metric), Bar Position (static, variable), Block (1,2,3,4), and VF (LVF, RVF) was performed on error rate. It should be noted that overall error rate was very low (4%), so some of the variations noted in this ANOVA do not represent very large deviations in performance level. This analysis revealed a main effect of Decision ($F(1, 30) = 26.52, p < 0.0001$) because there were fewer errors on categorical (2.4%) than metric trials (5.5%), consistent with faster RT on categorical than metric trials. The only significant two-way interaction was that of Block by Visual Field ($F(3, 90) = 2.87, p < 0.05$), which resulted because there was a lower error rate for RVF trials (2.9%) than for LVF trials (4.9%) for block 2 ($F(1, 30) = 7.23, p < 0.025$) but for no other block. This effect was moderated by a significant Decision by Block by VF interaction ($F(3,90) = 2.88, p < 0.05$), which revealed that the effect in the two-way Block by Visual Field interaction was due entirely to the metric condition ($F(1, 30) = 7.14, p < 0.025$) and not to the categorical condition ($F(1, 30) = 0.168, p = 0.68$). Because this effect is limited to block 2, it does not pose problems of interpretation of the Deci-

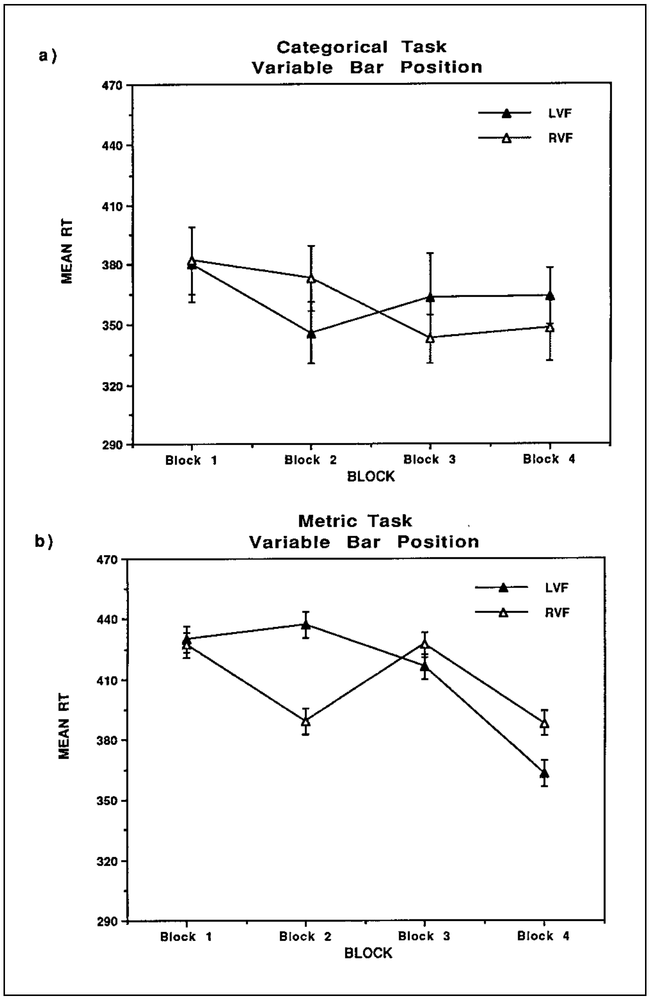

Figure 3. Performance as measured by mean RT from stimulus offset on the (a) categorical task and (b) metric task for LVF & RVF trials when the bar's position was variable.

sion by Block by VF interaction in the RT data in which the effects of interest were restricted to blocks 3 and 4.

There were a number of interactions in the accuracy data that were not significant in the RT analysis. However, none of these compromise interpretation of the RT data. There was a significant Decision by Bar Position by VF interaction ($F(1, 30) = 5.25, p < 0.05$), which resulted because for LVF trials there was an interaction of Decision by Bar Position ($F(1, 30) = 6.11, p < 0.025$), which did not occur for RVF trials ($F(1, 30), p = 0.675$). More specifically, for LVF categorical trials, the error rate was lower when the bar's position was variable (1.7%) rather than static (3.4%) ($p < 0.025$), whereas no difference was observed for the metric task (variable, 5.9%; static, 5.1%). This interaction was modified by a significant Hemispheric Bias by Decision by Bar Position by VF interaction ($F(1, 30) = 5.64, p < 0.025$), which indicated that the lack of any effect on RVF trials occurred because the two bias groups exhibited opposite patterns on the metric condition. For the LH group, the error rate on trials in which the bar's position was variable (3.7%) was lower than when it was static (6.2%), whereas for the RH group, the error rate on trials in which the bar's position was variable (6.9%) was greater than when static (4.7%), even though neither difference was statistically significant. There also was a significant Bar Position by Block by VF interaction ($F(3, 90) = 2.82, p < 0.05$) that occurred because when the bar's position was variable, there was a significantly lower error rate for RVF (1.8%) than for LVF trials for block 2 (5.3%) ($p > 0.01$) but no such difference was observed for the average of blocks 3 and 4 (RVF 4.1%; LVF 3.2%). No differences for the static condition were noted. Finally, there was a significant Hemispheric Bias by Decision by Block interaction ($F(3, 90) = 3.28, p < 0.025$). The pattern of this interaction was that, for both groups, error rates on categorical trials did not vary over blocks, but for metric trials, error rates increased for the LH group over blocks, whereas for the RH group, they declined.

Bihemispheric Trials

Reaction Time

A repeated-measures ANOVA with the between-subjects factor of Hemispheric Bias (RH, LH) and the within-subjects factors of Decision (categorical, metric), Bar Position (static, variable), Block (1,2,3,4) and Visual Field (BVF, CVF) was performed. These results yielded the same three main effects as observed for unilateral trials. A main effect of Decision ($F(1, 30) = 31.96, p < 0.0001$), a main effect of Bar Position ($F(1, 30) = 16.97, p < 0.0005$), and a main effect of Block ($F(3, 90) = 10.52, p < 0.0001$). Just as for unilateral trials, responses were faster to categorical (336 msec) than metric trials (402 msec), faster when the bar's position was static (353 msec) rather than variable (385 msec), and slower in block 1 (391 msec) than in blocks 2 (368 msec), 3 (361 msec), or 4 (356 msec).

There was also a Decision by Bar Position interaction ($F(1, 30) = 5.31, p < 0.05$), which resulted because the advantage for trials in which the bar's position was static rather than variable was greater for categorical (47 msec; 313 versus 360 msec) than for metric decisions (19 msec; 392 versus 411 msec). This interaction approached but did not reach significance for the unilateral trials ($p = 0.07$), with effects in the same direction. As observed for unilateral trials, there was a significant Bar Position by Block interaction ($F(3, 90) = 3.18, p < 0.05$), which resulted because the decrease in reaction time over blocks was only marginally significant when the bar's position was static ($F(3, 90) = 2.57, p = 0.06$) (For blocks 1 through 4, respectively: 365, 350, 350, and 346 msec) but highly significant ($F(3, 90) = 9.70, p < 0.001$) when it was variable (for blocks 1 through 4 respectively: 417, 386, 372, and 366 msec).

There was also a Decision by VF interaction ($F(1, 30) = 5.02, p < 0.05$), which resulted because for categorical judgments, CVF trials were processed marginally more quickly (333 msec) than BVF trials (340 msec) ($F(1, 30) = 3.40$, $p = 0.075$), whereas for metric decisions, there was no significant difference (BVF trials, 400 msec; CVF trials, 403 msec) ($F(1, 30) = 0.693$, $p = 0.412$).

The Decision by Block by VF and the Bar Position by Decision by Block by VF interaction, which were significant for unilateral trials, were only marginally so for bihemispheric trials, ($F(3, 90) = 2.48$, $p = 0.07$) and ($F(3, 90) = 2.33$, $p = 0.08$), respectively. The pattern of this four-way interaction was such that there was no differentiation in reaction time between CVF and BVF trials when the bar's position was static, similar to the lack of VF effects observed for unilateral trials in this condition. For the variable condition, there was an advantage for BVF trials for the metric task and a CVF advantage for the categorical task for blocks 2 and 3, which dissipated by block 4 (see Figures 4 and 5).

Finally, the only effect involving Hemispheric Bias emerged in a significant interaction with Bar Position and Visual Field ($F(1, 30) = 5.13$, $p < 0.05$). The nature of this interaction was that the pattern for the LH and RH groups differed significantly. For the LH group, the advantage for trials with a static as compared to variable bar position was marginally greater ($F(1, 30) = 3.44$, $p = 0.07$) for the CVF trials (39 msec; 353 versus 392 msec) than for BVF trials (28 msec; 360 versus 388 msec). For the RH group, the advantage on BVF (37 msec; 347 versus 384 msec) exceeded that on CVF trials (28 msec; 350 versus 378 msec), but not significantly so ($F(1, 30) = 1.19$, $p = 0.18$).

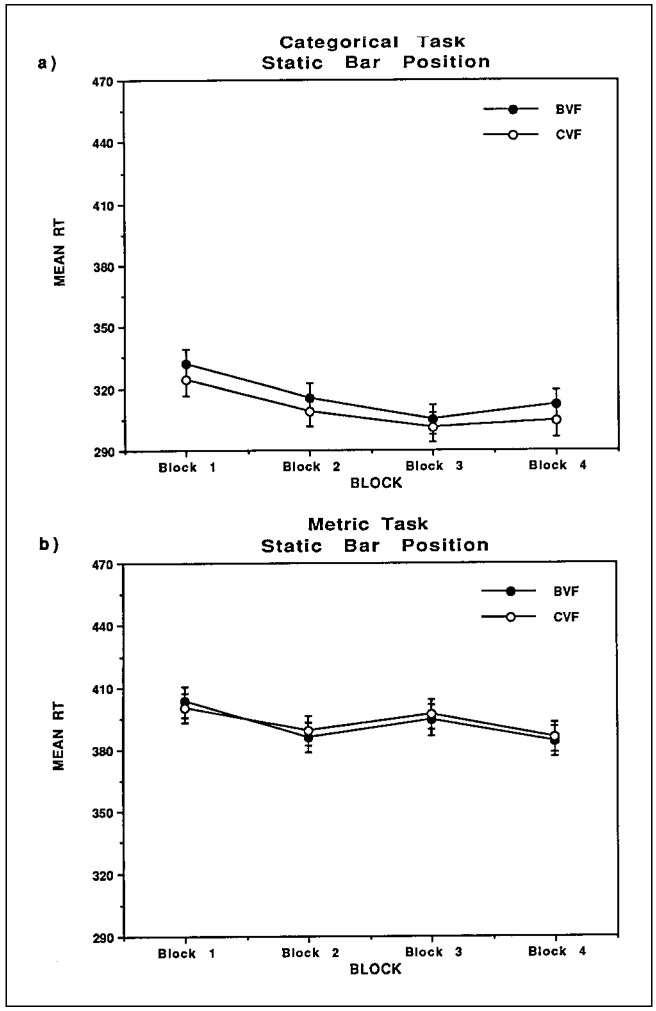

Figure 4. Performance as measured by mean RT from stimulus offset on the (a) categorical task and (b) metric task for BVF & CVF trials when the bar's position was static.

Error Rates

A repeated-measures ANOVA with the between-subjects factor of Hemispheric Bias (RH, LH) and the within-subjects factors of Decision (categorical, metric), Bar Position (static, variable), Block (1,2,3,4) and VF (BVF, CVF) was performed on error rates. This analysis revealed a main effect of Decision ($F(1, 30) = 19.19$, $p < 0.0001$), which resulted because the error rate to categorical decisions was significantly lower (1.9%) than to metric decisions (5.9%), consistent with the RT results. Once again, note the high degree of accuracy of responding.

In addition, there was a significant Decision by Block interaction ($F(3, 90) = 2.76$, $p < 0.05$) and a significant Bar Position by Block interaction ($F(3, 90) = 3.11$, $p < 0.05$), both of which were moderated by a significant Decision by Bar Position by Block interaction ($F(3, 90) = 3.10$, $p < 0.05$). This interaction indicated that error rates did not vary across blocks for the categorical trials ($F(1, 30) = 0.183$, $p = 0.683$) but did for the metric trials ($F(1, 30) = 14.04$, $p < 0.001$). However, the variation across blocks for metric trials was limited to the condition in which the bar's position was variable (mean error rates on blocks 1 through 4: 7.7, 9.5, 4.8, and 3.5%) ($F(1, 30) = 15.55$, $p < 0.0005$). Such a difference was not observed when the bar's position was static ($F(1, 30) = 0.104$, $p = 0.749$) (mean accuracy on blocks 1 through 4: 5.2, 5.3, 5.9, and 5.3% respectively). This interaction does not compromise any of the results observed in the RT analysis.

Comparison of Lateral and Bihemispheric Trials

To facilitate comparison with the findings of Hellige and colleagues, we examined whether the difference between metric and categorical processing for bihemispheric trials was similar to that observed on LVF trials or to that observed on RVF trials. Because the analysis of both unilateral and bihemispheric trials had indicated little differentiation in processing across VF (BVF, CVF, LVF, RVF) when the bar's position was static, our analysis was restricted to the condition in which the bar's position was variable.

We performed a repeated-measures ANOVA on mean RT with the between-subjects factor of Hemispheric Bias (RH, LH) and the within-subjects factors of Decision (categorical, metric), Block (1,2,3,4), and VF (BVF, CVF,

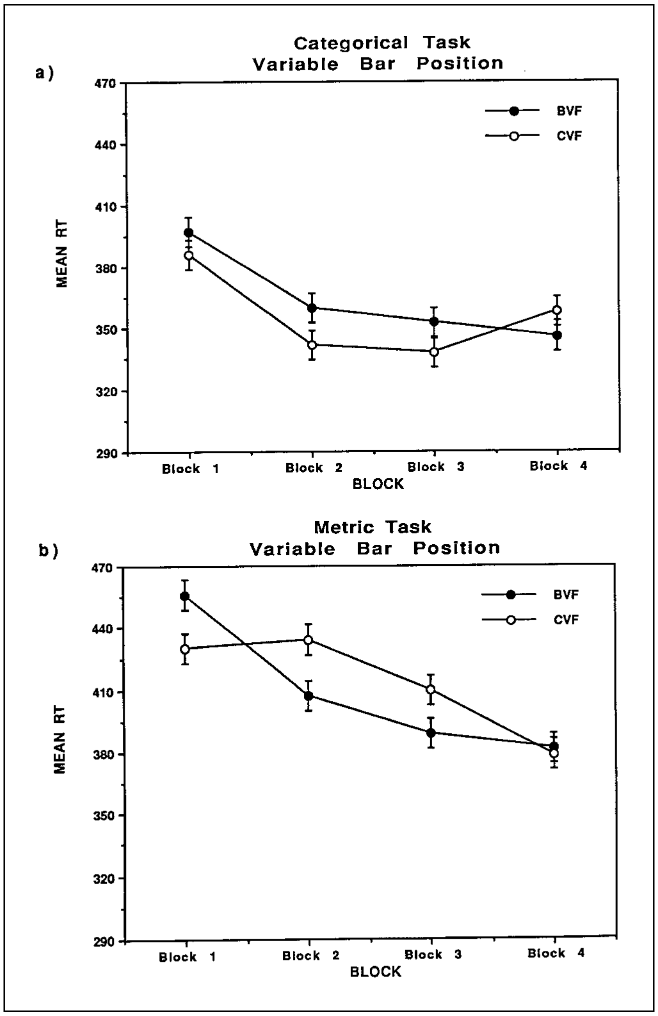

Figure 5. Performance as measured by mean RT from stimulus offset on the (a) categorical task and (b) metric task for BVF & CVF trials when the bar's position was variable.

LVF, RVF). Of importance, the interaction of Decision by Block by VF was highly significant ($F(9,270) = 4.279$, $p < 0.0001$). We concentrated our analyses on blocks 3 and 4, in which hemispheric asymmetries emerged. For these blocks, planned comparisons indicated that the difference in speed of responding between categorical and metric processing was greater for RVF trials (63 msec) than for LVF trials (26 msec) ($F(1, 30) = 12.97$, $p < 0.0025$). Planned comparisons indicated that the difference for BVF trials (35 msec) was similar to the difference observed in LVF trials and significantly different from that observed for RVF trials ($F(1, 30) = 4.80$, $p < 0.05$). Furthermore, planned comparisons indicated that the difference for CVF trials (47 msec) was similar to that observed for RVF trials and differed from that observed for LVF trials, although only marginally so ($F(1, 30) = 3.33$, $p = 0.078$). Thus, these analyses also suggest that BVF trials are processed like LVF trials, whereas CVF trials are processed like RVF trials. Tempering such a clear-cut distinction between processing on CVF and BVF trials, however, is the finding that differences in speed of responding to categorical and metric processing did not differ significantly for these two conditions ($F(3,270) = 1.08$, $p = 0.31$).

Finally, planned contrasts on this interaction indicated that for blocks 3 and 4, performance on bihemispheric trials was not superior to RVF trials for the categorical task or to LVF trials for the metric task. Thus, there was no redundancy gain for having two items appear on the screen (as occurred for BVF trials), nor was there faster responding because information was presented foveally (as occurred for CVF trials) as compared to laterally.

DISCUSSION

Our experiment had three major objectives: to determine whether a difference between categorical and metric spatial processing could be demonstrated under conditions in which an external reference frame would be difficult to use, to compare bihemispheric processing on CVF and BVF trials for the categorical and metric tasks, and to determine the degree to which individual differences in asymmetric hemispheric activation would influence the processing of spatial processing. We now discuss each of these issues in turn.

Hemispheric Differences in Spatial Processing

We did obtain evidence that the hemispheres are differentially adept at different types of spatial processing, but such evidence was limited to a condition that was likely to force spatial relations to be computed on each trial (i.e., when the bar's position was variable). In contrast, in a condition in which such continual computation was less likely and the task was easier (i.e., when the bar's position remained static), little differentiation of spatial processing between the hemispheres was observed.

The pattern of results observed when the bar's position was variable was consistent with Kosslyn's theory; there was a clear interaction between hemisphere (as indexed by RVF and LVF trials) and decision (metric, categorical), although it was only observed for the last two blocks of trials. For these blocks, we found a significant RVF advantage for the categorical task and a nonsignificant LVF advantage for the metric task. This pattern of results stands somewhat in contrast to the interaction typically observed by other researchers, which is a nonsignificant RVF advantage for the categorical condition and a significant LVF advantage for the metric task, although this advantage may dissipate over blocks (e.g., Hellige & Michimata, 1989; Kosslyn et al., 1989). Our finding that the manipulation of reference frame affected left-hemisphere processing more than right-hemisphere processing seems consistent with reports in the literature suggesting that left-hemisphere damage disproportionately affects individuals' abilities to use reference frames appropriately (Humphreys & Riddoch, 1984).

Our success in observing VF effects in the final two blocks of the experiment suggests that the manipulation designed to discourage the use of an external reference frame may indeed have addressed a crucial reason why VF effects dissipated with practice in previous experiments. However, the actual pattern of performance we observed across blocks was not that of a sustained VF effect in the direction of Kosslyn's hypothesis. Rather, processing in block 1 was very similar in both visual fields for both the categorical and metric tasks. The results from block 2 were striking; performance in the two visual fields in both tasks was *opposite* that predicted. This pattern was unexpected and warrants further investigation. Finally, after what seems like a switch in strategy, performance in the expected direction was observed in block 3 and maintained in block 4.

The lack of hemispheric differences for categorical versus metric spatial processes observed in our experiment when the bar remained in a static position across trials is consistent with the report of Sergent (1991, Experiments 1, 2, and 3). However, this finding is at odds with others who have observed a difference, such as Kosslyn et al. (1989) and Hellige and Michimata (1989). The reasons for this inconsistency across studies are not clear.

Bihemispheric Processing

The results from the bihemispheric trials provide some converging evidence for Kosslyn's conjecture that the size of a visual receptive field or the size of the attentional window might influence the facility with which certain types of spatial processing can occur. More specifically, he suggested that categorical spatial processing may rely more on cells with smaller receptive field sizes or may be compatible with a bias toward a smaller focus of attention and that metric processing may rely more on cells with larger receptive fields or be compatible with a bias toward a larger focus of attention. Hence, we predicted that the relative advantage of categorical over metric processing should be greater for CVF than BVF trials. This result would be excepted because categorical processing should be aided by central vision, where receptive fields are smaller and attention would probably be more tightly focused than would occur for lateral vision, which relies on cells that have larger receptive fields, and which would require a broader distribution of attention. Our results were consistent with this prediction.

Other aspects of our results also suggest an association between LVF and BVF processing that is distinct from an association between RVF and CVF processing. First, even though the difference in speed of processing between metric and categorical trials did not differ significantly for BVF and CVF trials, the size of the metric/categorical difference for LVF trials was similar to BVF trials and marginally significantly different from CVF trials. Conversely, the difference for RVF trials was similar to that observed for CVF trials and significantly different from RVF trials. Second, asymmetric hemispheric activation was revealed to have similar effects on LVF and BVF trials and also to act similarly on RVF and CVF trials. For unilateral trials, the greatest differentiation in processing between the categorical and metric decisions was observed for the VF contralateral to the more activated hemisphere. Thus, the distinction between categorical and metric processing was greater in the LVF for RH-biased individuals and in the RVF for LH-biased individuals. For bihemispheric trials, the RH-biased group was most sensitive to the decision manipulation on BVF trials, whereas the LH-biased group was most sensitive on CVF trials, indicating an association between LVF and BVF processing for the RH group and an association between RVF and CVF processing for the LH group. One might have predicted such results based on Kosslyn's conjecture about the role that receptive field size or attentional focus plays in processing spatial relations. To the degree that the RH-biased group relies on the right hemisphere, which is thought to be more adept at coarse coding and is suggested to have a larger attentional focus, one might have anticipated that these individuals would be more sensitive to manipulations on BVF trials (in which the information is located in an area with larger receptive fields and requires more distributed attention) than on CVF trials (in which the information is located in an area with smaller receptive fields in an area of space associated with more tightly focused attention). Conversely, the LH-biased individuals were more sensitive to spatial manipulations on CVF than BVF trials, consistent with the conjectured sensitivity of the left hemisphere for more fine-grained visual processing.

With regard to bihemispheric processing, the pattern we observed on BVF trials stands in direct contrast to that observed by Hellige and Michimata (1989). They found that the pattern of performance on BVF trials looked akin to that on RVF trials in that the size of the advantage of categorical over metric processing was equivalent for these two types of trials and greater than observed on LVF trials. In contrast, we found, as would be predicted by the receptive field hypothesis of Kosslyn, that the pattern on BVF trials was more akin to that on LVF trials, with an advantage for metric over categorical processing trials. How are we to explain this discrepancy between the two experiments? There are various possibilities. First, we had roughly equal numbers of individuals in the RH- and LH-biased group. Hellige's sample was unselected for asymmetric hemispheric activation, so it might be possible that his sample was disproportionately composed of individuals who are LH-biased. A more probable explanation is that our methods differed from Hellige's in two important ways. First, the association we found between BVF and LVF processing was observed for a condition in which the bar's position was variable as opposed to the static position in Hellige's studies. Hellige and colleagues have found that stimulus parameters can modify the degree to which processing on BVF trials mimics performance on unilateral trials. For example, when CVCs are presented vertically and laterally, performance on BVF trials is similar to that of LVF trials. This similarity is reduced if the CVCs are oriented horizontally and presented centrally (Hellige & Cowin, 1996). Second, we included CVF trials as well as BVF trials, whereas Hellige and colleagues only employed BVF trials. It may be that inclusion of both types of trials somehow modifies the cerebral balance of power so that we did not observe the same type of metacontrol as did Hellige and Michimata (1989). Supporting such a possibility, it is known that laterality effects can be sensitive to the context in which a stimulus appears (e.g., Christman et al., 1991).

Hemispheric Activation

The overall effects of asymmetric hemispheric activation are somewhat different than we might have anticipated based on previous findings. Levy et al. (1983a) suggested that greater activation of one hemisphere would induce an attentional bias to the contralateral visual field and that this heightened attention would yield better performance for that visual field. Using such logic, one might have expected the RH-biased group to exhibit superior performance on the metric than the categorical task, especially for LVF trials, and that the opposite would be true for the LH-biased group—that is, they would perform better on categorical than metric decisions, especially for RVF trials. Such a pattern of performance, however, was not observed. Rather, asymmetric hemispheric activation appeared to affect performance by augmenting the effects of task demands in the VF contralateral to the more activated hemisphere. Thus, in the current experiment, information in the visual field opposite the more activated hemisphere seems to be more susceptible or sensitive to task demands but does not predict the direction or degree to which those task demands influence the speed or accuracy of processing.

In sum, our study provides some support for Kosslyn's theory, both with regard to hemispheric differentiation of metric and categorical processing and with regard to the conjecture that the underpinnings of such a differentiation may be related to receptive field sizes or attentional biases. Our results, however, also demonstrate that this effect may be influenced by a number of task-related variables. It may be that to observe hemispheric differences a continual computation of spatial relations between two items needs to be made. Shifting the position of the bar might preclude using the computer screen as a reference frame and thus require that for both categorical and metric decisions, the relationship between the salient items—the bar and the dot—had to be calculated on every trial. Another possibility is that the differentiation between metric and categorical spatial processing is most likely to be observed when the task is more demanding and difficult. For example, Sergent (1991a) only observed differences when luminance was low (Experiment 4), which has the effect of making the task more difficult, as least as indexed by an elongation in mean RT relative to those experiments in which the luminance was higher (Experiments 1 and 2). We similarly found evidence for a differentiation in processing between the hemispheres in the condition that appeared to be more difficult (at least as indexed by longer RT and higher error rates), namely, when the bar's position was variable. Adding more complexity to the situation, it also appears that differentiation of these spatial processing may be influenced by certain aspects of individual differences, such as asymmetric hemispheric activation. Finally, it may be, as suggested by Kosslyn et al. (1994), that attentional demands play an important role in the pattern observed. Keeping the bar in a static position across trials may allow for the strategic employment of attention in a way that is quite distinct from that which occurs when the bar's position can vary across trials. Thus, while accumulating evidence seems to support a general difference in hemispheric facility for processing categorical and metric spatial relations, this differentiation interacts strongly with and seems highly dependent on stimulus parameters, task conditions, and the use of cognitive strategies. Further systematic investigations of these variables seem necessary to determine the nature of this hemispheric difference and its broader relevance to human behavior.

METHODS

Subjects

Thirty-two undergraduate volunteers (16 women and 16 men) participated either for course credit or for pay. All were screened to ensure normal or corrected-to-normal visual acuity and none had a lateral phoria. In addition, all were native speakers of English and all wrote with the right hand and used the right hand predominantly for eight common tasks (e.g., throwing a ball, hammering a nail). Individuals were classified with regard to asymmetric hemispheric activation (RH-biased, LH-biased) through use of the chimeric face test. In this test, an individual views 36 pairs of mirror-imaged chimeric faces in free vision. Each chimera is composed of a smiling half-face and a neutral half-face. The participant must decide which of the two chimeras looks happier. An asymmetry score is calculated by determining the number of faces chosen on which the smiling half-face is on the right as compared to the left, divided by the total [(R − L)/36]. Levy et al. (1983b) found that the average score for 111 right-handers on this test was −0.303. Thus, if an individual had a score less than −0.303, he or she was classified as RH-biased. This procedure resulted in 14 individuals who were classified as RH-biased and 18 who were classified as LH-biased.

Apparatus and Stimulus Materials

At the beginning of the experiment, handedness was assessed, vision was screened, and individuals were given the chimeric face test to determine their asymmetric hemispheric activation. Afterward, participants were seated approximately 60 cm from a Macintosh Performa 650. To ensure constant viewing conditions across participants, individuals placed their chin in a chin rest and their forehead against a stabilization bar. SuperLab 1.6.8 software was used to present the stimuli and to record reaction time and response accuracy.

The stimuli presented on the computer screen consisted of a black bar and dot on a white background and were modeled after those used by Hellige and Michimata (1989) and Kosslyn et al. (1989) (see Figure 6). The stimulus bar subtended approximately 1.4° of horizontal visual angle and the dot subtended approximately 0.2° of visual angle. The dot was located in one of 12 possible positions with respect to the bar, subtending 0.5, 1, 1.5, 2, 2.5, 3, and 3.5° of visual angle above or below the bar. Six dot positions were further than 2.5 cm from the bar (three above and three below), whereas another six were located within 2.5 cm of the bar. In the static condition, the position of the bar was constant, being aligned at vertical midline. In the variable condition, the bar could be presented either at vertical midline, 2° above vertical midline, or 2° below. On a given trial, the bar/dot pair was either presented in the center of the screen (CVF trials), 2° to the left of fixation (LVF trials), 2° to the right of fixation (RVF trials), or simultaneously 2° to the left and 2° to the right of fixation (BVF trials).

Stimuli were counterbalanced so that each dot bar pair occurred equally often across all trials and across the different visual field conditions. Furthermore, in the variable condition, each bar/dot pair (12 total) appeared once with each of the bar position (three positions) in each visual field condition (four conditions) for a total of 144 trials, which were divided into four 36-trial blocks. In the static condition, each bar/dot pair (12 pairs) appeared four times in each visual field condition (four visual field conditions) for a total of 192 trials, which were divided into four 48-trial blocks.

Procedure

Each individual participated in two experimental sessions separated by approximately 48 hr. In the first session, the participants performed the categorical task, in which they decided whether the dot was above or below the bar. In the second, they performed the metric task, in which they decided whether the dot was within 2.5 cm of the bar or 2.5 cm beyond. We used this fixed order to replicate the methods of Hellige and Michimata (1989), who had employed such a method to better enable an examination of individual differences by holding any carryover or order effects constant across individuals. Within each session, individuals were given eight blocks of trials: in four the position of the bar was static and in four it varied across the three positions randomly. The order of blocks (fixed/variable versus variable/fixed) was counterbalanced across individuals with regard to both gender and asymmetric hemispheric activation (RH bias, LH bias). The order of conditions (fixed/variable or variable/fixed) was the same for an individual for both the categorical and metric decisions. Stimuli within blocks were presented to individuals in a random order.

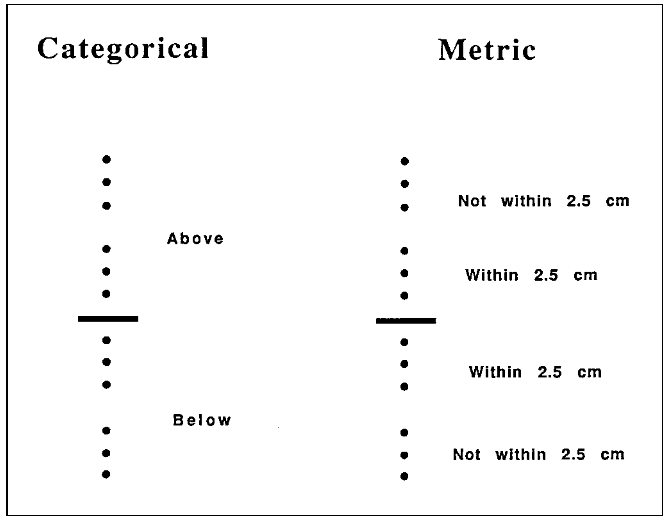

Figure 6. The position of the bar and the 12 possible locations of the dot.

At the start of each experimental session, individuals were given instructions for the task. Individuals were shown the bar with the 12 possible locations of the dots on a display that indicated which were above and below the line for the categorical task and which were within 2.5 cm and which were further beyond for the metric task. For the categorical task, participants were instructed to indicate as quickly and as accurately as possible whether the dot was above or below the line, regardless of distance. For the metric tasks, individuals were instructed to make a decision as to whether the dot was within 2.5 cm of the bar or beyond, irrespective of whether the dot was above or below the bar.

Participants were told to indicate their response by hitting one of two keys on a keyboard, either g or h. Assignment of key to response (e.g., g for above, h for below) was counterbalanced across individuals. Participants responded by using the index and middle finger of one hand. Within each task/condition combination (e.g., categorical/variable, metric/static), half of the blocks were responded to with one hand and the other half of the blocks, with the other hand. The order of hand usage was balanced across task/condition combinations across individuals. No practice trials were given because practice had been previously found to dissipate hemispheric effects and because task instructions were easily understood.

On each trial, the fixation cross appeared on the screen for 2000 msec, followed by a blank white screen for 50 msec, and then the fixation cross again for 200 msec. The flashing of the fixation cross was designed to draw the individual's attention to fixation. Afterward the stimuli appeared for 150 msec, followed by a blank white screen, which remained on until the individual made his or her response. Response times were measured from stimulus offset. The end of each block was indicated by an instruction screen, and individuals were allowed to relax and then advised to switch responding hand as appropriate. No feedback was given to participants with regard to either response accuracy or reaction time.

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