Hemispheric Processing of Categorical and Coordinate Spatial Relations in the Absence of Low Spatial Frequencies

Matia Okubo[1] and Chikashi Michimata[2]

Abstract

■ Right-handed participants performed the categorical and coordinate spatial relation judgments on stimuli presented to either the left visual field—right hemisphere (LVF-RH) or the right visual field—left hemisphere (RVF-LH). The stimulus patterns were formulated either by bright dots or by *contrast-balanced dots*. When the stimuli were bright, an RVF-LH advantage was observed for the categorical task, whereas an LVF-RH advantage was observed for the coordinate task. When the stimuli were contrast balanced, the RVF-LH advantage was observed for the categorical task, but the LVF-RH advantage was eliminated for the coordinate task. Because the contrast-balanced dots are largely devoid of low spatial frequency content, these results suggest that processing of low spatial frequency is responsible for the right hemisphere advantage for the coordinate spatial processing. ■

INTRODUCTION

Kosslyn (1987) proposed that the brain computes two kinds of spatial relations in different systems. One is called categorical spatial relationship, which assigns a category such as "above/below" or "left/right" to a spatial relation. The other is called coordinate spatial relationship, which represents precise distance and location in a metric coordinate system. He hypothesized that the left and right hemispheres efficiently process the categorical and coordinate spatial relations, respectively. This hypothesis was supported by a number of visual half-field studies: The right visual field—left hemisphere (RVF-LH) advantage has been found for the categorical spatial relation judgment, whereas the left visual field—right hemisphere (LVF-RH) advantage has been found for the coordinate spatial relation judgment (e.g., Michimata, 1997; Rybash & Hoyer, 1992; Hellige & Michimata, 1989; Kosslyn et al., 1989).

On the other hand, several studies demonstrated that, at some level of processing beyond the visual cortex, the left and right hemispheres preferentially process visual information carried by channels tuned to relatively high and low spatial frequencies, respectively (e.g., Chiristman, Kitterle, & Hellige, 1991; Kitterle, Chiristman, & Hellige, 1990; Kitterle & Selig, 1991; Kitterle, Hellige, & Chiristman, 1992; Sergent, 1983; Sergent & Hellige, 1986).

For the purpose of the present study, it is important to note that Kosslyn, Chabris, Marsolek, and Koenig (1992) suggested that the hemispheric difference for categorical and coordinate processing can be directly linked to processing of spatial frequency. In a simulation study, they found that networks that receive input from smaller receptive fields, which encode high spatial frequency effectively, computed categorical spatial information efficiently, whereas networks that receive input from larger receptive fields, which encode low spatial frequency effectively, computed coordinate spatial information efficiently via *coarse coding mechanisms*. Kosslyn et al. (1992) hypothesized that the left hemisphere is predisposed toward efficient use of information from channels responding to high spatial frequency and, hence, processes the categorical spatial relation efficiently. In contrast, the right hemisphere is predisposed toward efficient use of information from channels responding to low spatial frequency and, hence, processes the coordinate spatial relation efficiently (for critique and additional discussion see Baker, Chabris, & Kosslyn, 1999; Cook, 1995; Cook, Fruh, & Landis, 1995; Kosslyn, Chabris, & Baker, 1995; Kosslyn, Chabris, Marsolek, Jacobs, & Koenig, 1995).

There are few studies that empirically examined Kosslyn et al.'s (1992) proposition. For example, Cowin and Hellige (1994) tested the role of high spatial frequency for the categorical processing in the cerebral hemispheres by removing high spatial frequency via dioptic blurring. While they found that blurring disrupted the performance of the categorical task, they failed to obtain

[1]University of Tokyo, [2]Sophia University

the visual field difference for it. It is not advisable for Cowin and Hellige to focus on the categorical processing because a number of studies have failed to obtain the significant RVF-LH advantage for the categorical task (e.g., Michimata, 1997; Rybash & Hoyer, 1992; Sergent, 1991; Hellige & Michimata, 1989).

On the other hand, Roth and Hellige (1998) tested the effect of red background on the coordinate processing in the two hemispheres. It is reported that the red background selectively attenuates the cell's activity in the magnocellular pathway (see Livingstone & Hubel, 1984). Recent studies have demonstrated that the magnocellular pathway is the physiological basis of the low spatial/high temporal frequency channel (Michimata, Okubo, & Mugishima, 1999; Breitmeyer & Willams, 1990; Breitmeyer, May, & Heller, 1991; Breitmeyer & Breier, 1994). Therefore, the red background should attenuate processing of low spatial frequency. Roth and Hellige obtained a Task × Visual Field interaction in the predicted direction. However, the red background did not affect the interaction; rather it attenuated the overall coordinate processing. These results are difficult to interpret in terms of spatial frequency processing because they did not directly manipulate spatial frequency. It seems clear that further empirical tests are needed to evaluate the validity of Kosslyn's proposal.

The purpose of the present study was to test the role of spatial frequency for the LVF-RH advantage for the coordinate processing via direct manipulation of spatial frequency. This was achieved by employing the stimulus patterns composed of *contrast-balanced dots*, which were known to be devoid of low spatial frequency content (see Lamb & Yund, 1993; Hughes, Fendrich, & Reuter-Lorenz, 1990). A contrast-balanced dot consists of a small bright spot surrounded by a darker annulus (see Figure 1). The luminance of the center spot and the darkness of the surround are chosen to produce a space-averaged luminance, which equals the luminance of the background. According to Hughes et al. (1990), contrast balancing removes almost all the power below about 3.0 cycles per degree for the pixel size they used (i.e., 2 arc/min). One might argue that more direct manipulation, such as low- or high-pass frequency filtering, is preferable. However, filtering is not used because it can severely degrade the percept. Various forms of perceptual degradation (e.g., blurring, overlay masks, decreasing luminance) have been shown to interfere with processing more when stimuli are presented to the RVF-LH than when stimuli are presented to the LVF-RH (e.g., Chiristman, 1990; Sergent, 1983; Sergent & Hellige, 1986). Because contrast-balanced dots are clearly visible at a standard viewing distance, the procedure does not produce the substantial degradation. For the control, we used the bright dots consisting of the bright center of the contrast-balanced dot.[1]

Based on Kosslyn et al.'s (1992) hypothesis, it is predicted that the LVF-RH advantage of the coordinate task will be selectively attenuated or eliminated when the stimuli are contrast balanced.

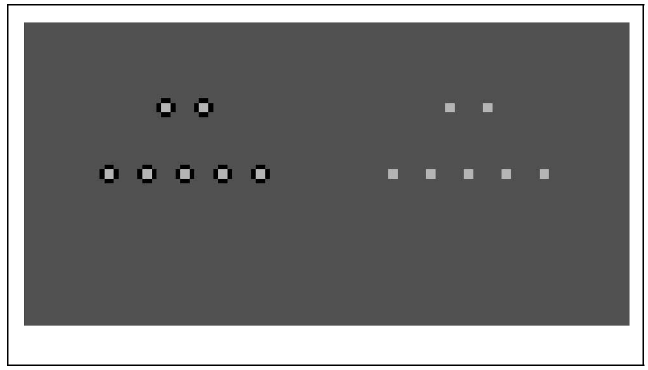

Figure 1. Examples of the stimulus: The stimulus pattern composed of the contrast-balanced dots was presented to the left and the one composed of bright dots was presented to the right. Both stimuli were judged to be above in the categorical task and to be near in the coordinate task.

RESULTS

For each participant, the median reaction times of correct responses and the percentage of errors were computed for the eight experimental conditions described in the Methods: Design section. The results of the two measures were similar and produced a high positive correlation ($r = +.86$). Thus, there was no evidence of speed–accuracy trade-off. In view of this, and because the percentage of errors was so small (4.00% and 5.79%, for the categorical and coordinate task, respectively), only the reaction time data will be presented.

Reaction time data was subjected to a 2 (task: categorical vs. coordinate) × 2 (visual field: LVF-RH vs. RVF-LH) × 2 (stimulus type: bright vs. contrast-balanced) repeated measures analysis of variance. Participants responded faster for the categorical task (582 msec) than for the coordinate task (667 msec), producing a significant main effect of task, $F(1,25) = 33.07$, $MSE = 11362.97$, $p < .001$. A main effect of stimulus type was also significant, $F(1,25) = 43.29$, $MSE = 1196.55$, $p < .001$, response being faster for the bright stimuli (604 msec) than for the contrast-balanced stimuli (644 msec). While a main effect of visual field was not significant ($F < 1.00$), there was a significant Task × Visual Field interaction, $F(1,25) = 17.44$, $MSE = 465.93$, $p < .001$. For the categorical task, responses were faster for the RVF-LH trials (574 msec) than for the LVF-RH trials (589 msec), whereas for the coordinate task responses were faster for the LVF-RH trials (662 msec) than for the RVF-LH trials (672 msec). This pattern was consistent with Kosslyn's (1987) prediction. A Visual Field × Stimulus Type interaction was also significant, $F(1,25) = 4.58$, $MSE = 464.65$, $p = .042$: For the bright stimuli, responses were faster for the LVF-RH trials (601 msec) than for the RVF-LH trials (608 msec), and for the contrast-balanced stimuli, responses were faster for the RVF-LH trials (638 msec) than for the LVF-RH trials (650 msec). These interactions were qualified by a significant Task × Visual Field × Stimulus Type interaction, $F(1,25) = 6.06$, $MSE = 651.55$, $p = .021$.

Figure 2 shows this three-way interaction: The Task × Visual Field interaction predicted by Kosslyn (1987) was observed for the bright stimuli (left panel), but not for the contrast-balanced stimuli (right panel). In fact, responses for the bright stimuli were faster for the categorical task (562 msec) than for the coordinate task (646 msec), producing a significant main effect of task, $F(1,25) = 35.86$, $MSE = 5050.05$, $p < .001$. The main effect of task was qualified by the significant Task × Visual Field interaction, $F(1,25) = 23.47$, $MSE = 498.35$, $p < .001$. Thus, the simple main effects of visual field was tested on each task: A significant RVF-LH advantage was found for the categorical task, $F(1,50) = 5.97$, $MSE = 449.29$, $p = .018$; LVF-RH = 570 msec; RVF-LH = 555 msec. In contrast, a significant LVF-RH advantage was found for the coordinate task, $F(1,50) = 22.78$, $MSE = 449.29$, $p < .001$; LVF-RH = 632 msec; RVF-LH = 660 msec.

On the other hand, responses for the contrast-balanced stimuli (right panel) were faster for the categorical task (601 msec) than for the coordinate task (687 msec), producing a significant main effect of task, $F(1,25) = 28.30$, $MSE = 6882.80$, $p = .008$. A main effect of visual field was not significant ($p = .12$). However, planned comparison revealed a significant RVF-LH advantage for the categorical task, $t(25) = 1.96$, $SE = 7.87$, $p = .03$, one-tailed; LVF-RH = 608 msec; RVF-LH = 593 msec, whereas there was no significant visual field difference for the coordinate task ($t < 1.00$). Different from the bright stimuli, the Task × Visual Field interaction was not significant ($F < 1.00$).

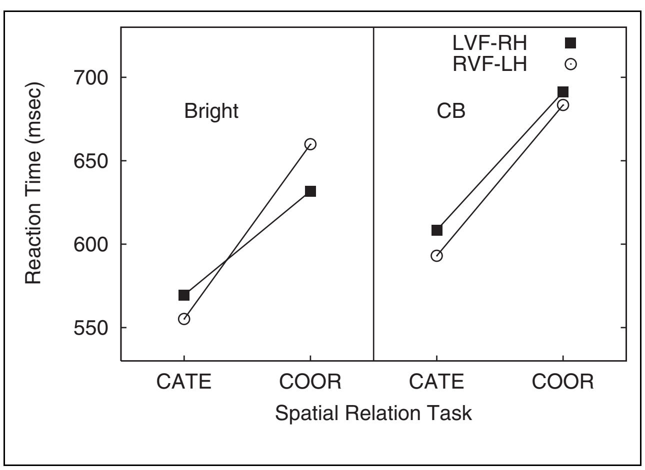

Figure 2. Mean median reaction times on the LVF-RH and RVF-LH trials as a function of spatial relation task. The results for the bright and contrast-balanced (CB) stimuli are presented in the left and right panels, respectively. CATE and COOR stand for categorical and coordinate, respectively.

DISCUSSION

The Task × Visual Field interaction observed for the bright stimuli was consistent with Kosslyn's (1987) hypothesis that the left and right hemispheres efficiently process the categorical and coordinate spatial relation, respectively. The statistically significant RVF-LH advantage for the categorical task was particularly impressive because a number of studies have failed to obtain it (e.g., Michimata, 1997; Rybash & Hoyer, 1992; Sergent, 1991; Hellige & Michimata, 1989). This can be explained in terms of spatial frequency content of the stimuli. Decreasing the size of a visual image increases the proportion of high-frequency compared to low-frequency components. The stimulus element in the present experiment (i.e., a small dot) was much smaller than that in the conventional dot-and-bar pattern. Thus, the component frequencies were higher in the stimuli used in the present experiment than those used in the previous studies. The RVF-LH advantage for the categorical processing might be more reliable when the stimulus elements are smaller.

The Task × Visual Field interaction disappeared when the stimuli were contrast balanced and devoid of low spatial frequency content: The LVF-RH advantage for the coordinate task was eliminated, whereas the RVF-LH advantage for the categorical task was intact. The result for the coordinate task is consistent with the hypothesis that processing of low spatial frequency contributes to the right hemisphere advantage for coordinate spatial processing, and it is the first and direct evidence that there is a direct link between processing of low spatial frequency and the hemispheric difference for the coordinate processing.

The result for the categorical task is also consistent with the hypothesis because there is no assumption on the relation between the RVF-LH advantage for categorical processing and low spatial frequency information. Rather, Kosslyn et al. (1992) argued that processing of high spatial frequency is responsible for the left hemisphere advantage for the categorical processing.

Besides eliminating the LVF-RH advantage for the coordinate task, the contrast balancing increased overall reaction times. This may imply that contrast balancing decreased general perceptibility of the stimuli. However, perceptual degradation usually disrupts the performance on the RVF-LH trials rather than on the LVF-RH trials (see Sergent, 1983; Sergent & Hellige, 1986). In contrast, the contrast balancing in the present experiment disrupted the performance on the LVF-RH trials rather than on the RVF-LH trials. Thus, the hemispheric effects of contrast balancing should not be interpreted from the viewpoint of the conventional degradation effect. The slower responses for contrast-balanced stimuli may be attributed to the temporal characteristics of spatial frequency channels and the frequency content of the contrast-balanced stimuli. It is well known that the low spatial frequency channels respond transiently, whereas the high spatial frequency channels respond sustainedly (e.g., Breitmeyer, 1975). Thus, processing may be slower for the contrast-balanced stimuli than for the bright stimuli because the former do not contain the component that produces transient responses.

The main effect of task indicated that the coordinate task was more difficult than the categorical task. One might question if the present results could be explained in terms of task difficulty. It is known that the LVF-RH advantage became more reliable with the difficulty of the coordinate task increased (Parrot, Doyon, Demonet, & Cardebat, 1999). In the present experiment, the LVF-RH advantage for the coordinate task disappeared for the contrast-balanced condition, which was more difficult than the bright condition. Thus, task difficulty cannot explain the three-way interaction observed in the present experiment.

The Task × Visual Field × Stimulus Type interaction is not consistent with the previous findings that manipulation of spatial frequency did not affect the Task × Visual Field interaction (Niebauer & Christman, 1999; Roth & Hellige, 1998; Cowin & Hellige, 1994). This discrepancy may be attributable to methodological problems in the previous studies. As stated in the Introduction, Cowin and Hellige (1994) did not obtain the critical hemispheric difference, and Roth and Hellige (1998) did not directly manipulate spatial frequency. Niebauer and Christman (1999) obtained a Task × Visual Field interaction, but this interaction was not affected by frequency content of the stimuli. These results are difficult to evaluate because their task (i.e., discrimination of spatial frequency) was radically different from the conventional categorical and coordinate tasks and the interaction can be explained in terms of task difficulty as they admitted: Hemispheric difference was found only for the coordinate condition in which responses were much slower and less accurate than for the categorical condition.

The present results are highly consistent with the prediction based on Kosslyn et al.'s (1992) computer simulation, but are also compatible with the double-filtering-by-frequency (DFF) theory proposed by Ivry and Robertson (1998). The DFF theory assumes that the left and right hemispheres efficiently process relatively high and low spatial frequency, respectively, within the range of frequency that is relevant for the task being performed. In the present experiment, the contrast-balanced and bright stimuli were presented in a random order. As participants could not predict the stimulus type on each trial, attention was directed to the broad range of frequency that was contained in the bright stimuli. For the broad range, contrast balancing could remove low spatial frequencies in the relative scale. The DFF theory can easily explain the absence of LVF-RH advantage for the coordinate task when relatively low frequencies were removed from the stimuli. To evaluate the validity of this account, the effect of random ordering should be tested in the future.

It is not easy to differentiate between Kosslyn et al.'s (1992) hypothesis and the DFF theory, and it is beyond the scope of the present study. Our findings are highly important for both theories to develop future research because the present experiment provides direct evidence for the idea that the processing efficiency for spatial frequency contributes to the hemispheric asymmetry for the spatial relation processing.

Conclusion

At first glance, hemispheric processing of spatial frequency and spatial relation have little relationship with each other. In fact, they have been usually discussed in different contexts. The present experiment succeeded in showing that there is a direct link between processing of low spatial frequency and the right hemisphere advantage for the coordinate processing. Additional research is needed to clarify the relationship between high spatial frequency, categorical relation, and the left hemisphere, and to test the effects of systematical manipulation of spatial frequency on spatial relation processing to draw more decisive conclusion. However, the present results suggest the possibility that the hemispheric differences for spatial frequency and spatial relation are different manifestations of the same underlying mechanisms, at least for the processing of low spatial frequency and coordinate spatial relation in the right hemisphere. It is suggested that the hemispheric differences for high-level visual processing (i.e., spatial relation processing) somehow depend on each hemisphere's ability to process low-level visual features like spatial frequency.

METHODS

Participants

Twenty-six undergraduate and graduate students (6 women, 20 men) served as paid participants. They all had normal or corrected-to-normal visual acuity and were unaware of the hypothesis under investigation. All of them were right-handed with no left-handed relatives in their immediate families. Handedness was assessed with a short questionnaire prior to the experiment.

Design

The experiment was a 2 (task: categorical vs. coordinate) × 2 (visual field: LVF-RH vs. RVF-LH) × 2 (stimulus type: bright vs. contrast balanced) factorial design. All variables were manipulated within participants. The dependent variable was reaction time.

Apparatus

A 17-in. CRT display (NANAO 56TS) and a personal computer (Macintosh Powerbook 5300) were used for the presentation of the stimuli and for recording participants' responses. The experiment was controlled by a MacProbe software package (cf. Hunt, 1994). A 10-key pad (Sanwa Supply NT-MAC 2) was connected to the computer and served as a four-key response console.

Stimuli

Examples of the stimulus used in the experiment are shown in Figure 1. The stimulus patterns were composed either of the contrast-balanced dots or the bright dots. The size and the luminance of these dots approximated those used by Hughes et al. (1990). Each contrast-balanced dot consisted of a bright center region of 2 × 2 pixels square and a 1-pixel–wide dark surround. The dots were rounded by removing the corner pixel from the dark surround, producing a 1:2 ratio of bright to dark pixels in each contrast-balanced dot. The bright dots, which were used as a control, consisted of the bright center region of the contrast-balanced dot. Each pixel subtended .36 mm. To achieve contrast balancing, the luminance was set to 19 cd/m^2 for the background, 58 cd/m^2 for the bright center, and 1 cd/m^2 for the dark surround. Consequently, the stimulus patterns composed of the contrast-balanced dots could not be seen from relatively long distances, where those of the bright dots were clearly visible, because the component frequencies of the contrast-balanced dots were preliminary high and surpassed the sensitivity range of the human visual system at a longer viewing distance.[2]

The configuration of the stimulus patterns was modeled after the dot-and-bar patterns used by Hellige and Michimata (1989). Each pattern was composed of seven dots. The horizontal separation between the bright region of the dots was set to six pixels. Five dots were aligned horizontally and subtended approximately 1.3° of visual angle. These five dots corresponded to the bar in the dot-and-bar pattern. Two other dots corresponded to the dot in the dot-and-line pattern. The two dots were aligned horizontally and were located in one of the 12 possible positions with respect to the five dots, subtending 0.5°, 1.0°, 1.5°, 2.5°, 3.0°, and 3.5° above or below the five dots.

The fixation dot positioned at the center of the display. It had the same size and luminance as the bright dot. Each stimulus pattern was presented to either the right or left visual field. The centermost dot of each pattern was 2° away from the fixation. The vertical position of the five dots was the same as the fixation.

Procedure

At the beginning, participants were told to keep the index and middle fingers of the left and right hand on the innermost and outermost response keys, respectively. They were told to direct their gaze toward the fixation when it appeared. Participants were told to maintain the eye fixation until after they had made their responses, and to respond as quickly and as accurately as possible.

For both tasks, participants were seated in a dark room approximately 57 cm away from the display with their head positioned by a chin rest. Each trial began with the onset of the fixation dot for 750 msec, followed immediately by the stimulus pattern for 150 msec. Participants made their responses by simultaneously pressing two keys by index or middle fingers. The finger-response mapping was counterbalanced across participants. Prior to each task, they received four practice trials to become familiar with the experimental procedure.

All participants performed the categorical task first, followed by the coordinate task. For the categorical task, participants indicated whether the two dots were above or below the five dots, with the distance between the dots being irrelevant. For the coordinate task, participants indicated whether the two dots were near to or far from the five dots. Prior to the coordinate task, participants were told that the distances within 2 cm should be responded as *near*, and the distances beyond 2 cm should be responded as *far*.

The order of the task was not counterbalanced for the following reasons. It has been reported that the LVF-RH advantage for the coordinate task is decreased and eliminated with practice (e.g., Michimata, 1997; Rybash & Hoyer, 1992; Hellige & Michimata, 1989; Kosslyn et al., 1989). The number of practice trials, therefore, should be as small as possible. However, pilot data indicated that it was very difficult for naive participants to perform the coordinate task with the unusual four-key response procedure without substantial practice, whereas it was relatively easy to perform the categorical task with little practice. Thus, participants performed the categorical task first in order to become familiar with the response procedure and the experimental settings without performing the coordinate task. It might be possible that the task performed second may suffer from negative transfer for the stimulus–response mapping or might benefit from practice with the task performed first. However, responses for the categorical task (i.e., above/below) and for the coordinate task (i.e., near/far) were orthogonal and conceptually distinct. The responses, therefore, may not be confounded, and the practice may have little effect on the spatial relation processing per se. In fact, the order of the categorical and coordinate tasks neither produced significant main effects, nor interacted with the effect of visual field and the Task × Visual Field interaction in the previous studies (e.g., Michimata, 1997). Thus, there would be good reasons to assume that our results were not affected by the fixed task order.

Participants received a total of 288 trials, which were divided into six blocks of 48 trials consisting of an orthogonal combination of 12 possible dot position, two visual field, and two stimulus type conditions. The stimuli were presented to participants in different random orders. Participants received a short break after each trial block.

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Reprint requests should be sent to Matia Okubo, Department of Psychology, Graduate School of Humanity and Sociologies, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan, or via e-mail: matia@zoo.L.u-tokyo.ac.jp.

Notes

1. It is possible to use either a bright center region or a dark surround region. The bright center was used for the following reasons. First, it contains broadband spatial frequencies. Second, if the dark surround region was used, the effect of removing frequencies can be confounded with that of the perceptual degradation by low luminance (Sergent, 1991; Chiristman, 1990).
2. The luminances used in the present experiment were slightly different from those that achieve optimal contrast balancing (e.g., 1, 20, and 58 cd/m^2, for surround, center, and background, respectively). When these optimal values were used, the contrast-balanced dots remained visible at a distance. The luminances were slightly adjusted so that the screen appeared a uniform gray when viewed from a distance, as were done by Hughes et al. (1990).

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