The Role of High Spatial Frequencies in Hemispheric Processing of Categorical and Coordinate Spatial Relations

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Abstract

■ Right-handed participants performed categorical and coordinate spatial relation tasks on stimuli presented either to the left visual field-right hemisphere (LVF-RH) or to the right visual field-left hemisphere (RVF-LH). The stimuli were either unfiltered or low-pass filtered (i.e., devoid of high spatial frequency content). Consistent with previous studies, the unfiltered condition produced a significant RVF-LH advantage for the categorical task and an LVF-RH advantage for the coordinate task. Low-pass filtering eliminated this Task × Visual Field interaction; thus, the RVF-LH advantage disappeared for the categorical task. The present results suggest that processing of high spatial frequency contributes to the left hemispheric advantage for categorical spatial processing. ■

INTRODUCTION

The brain computes at least two types of spatial relations to represent our visual environment. One is called a *categorical spatial relationship*, which assigns a category, such as "above/below" or "left/right," to a spatial relation. The other is called a *coordinate spatial relationship*, which represents distance and location in a metric coordinate system. Categorical and coordinate spatial relations play an important role in high-level visual processes, such as object recognition and face recognition (e.g., Cooper & Wojan, 2000; Laeng, Shah, & Kosslyn, 1999; Kosslyn, 1994).

Kosslyn (1987) hypothesized that the left hemisphere efficiently processes categorical spatial relations and the right hemisphere efficiently processes coordinate spatial relations. This hypothesis was supported by numerous visual half-field experiments (for reviews, see Jager & Postma, 2003; Laeng, Chabris, & Kosslyn, 2003). A right visual field-left hemisphere (RVF-LH) advantage has been found for categorical tasks (e.g., "Is a dot above or below the bar?"), whereas a left visual field-right hemisphere (LVF-RH) advantage has been found for coordinate tasks (e.g., "Is a dot within 2 cm of the bar?").

Kosslyn, Chabris, Marsolek, and Koenig (1992) proposed the possible relationship between processing of spatial relations and processing of spatial frequency. Their computer simulations suggest that categorical spatial relations are processed efficiently by small non-overlapping receptive fields, which effectively encode high spatial frequency, because these fields can carve input space into discrete bins. On the other hand, coordinate spatial relations are processed efficiently by large overlapping receptive fields via coarse coding mechanisms, and these receptive fields effectively encode low spatial frequency (see also Baker, Chabris, & Kosslyn, 1999; Jacobs & Kosslyn, 1994). It is known that high and low spatial frequencies are efficiently processed by the left and right hemispheres, respectively (e.g., Ivry & Robertson, 1998; Kitterle, Hellige, & Christman, 1992; Kitterle & Selig, 1991; Kitterle, Christman, & Hellige, 1990; Sergent, 1982, 1983), although these results were not always supported (for a review, see Grabowska & Nowicka, 1996). Therefore, Kosslyn et al. (1992) hypothesized that the right hemisphere's efficiency for processing of low spatial frequency contributes to the right hemispheric advantage for processing coordinate spatial relations, whereas the left hemisphere's efficiency for processing of high spatial frequency contributes to the left hemispheric advantage for processing categorical spatial relations.

Recently, we examined the role of low spatial frequency in hemispheric processing of spatial relations using a contrast-balancing technique (Okubo & Michimata, 2002). The LVF-RH advantage for the coordinate task was selectively eliminated when low spatial frequencies were removed, whereas the RVF-LH advantage for the categorical task was intact. These results suggest that processing of low spatial frequency contributes to coordinate spatial processing in the right hemisphere.

Cowin and Hellige (1994) used dioptic blurring to examine the role of high spatial frequency in categorical

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spatial processing. To attenuate higher spatial frequencies, participants observed the dot-and-bar stimuli through eyeglasses with +3 diopter lenses. Cowin and Hellige found that blurring disrupted the categorical task, but not the coordinate task. This finding supports the idea that categorical spatial relations were efficiently processed by use of high spatial frequency. However, the effects of blurring did not differ between the LVF-RH and RVF-LH trials of the categorical task. Cowin and Hellige concluded that these results do not support the idea that the two hemispheres rely on different aspects of spatial frequencies to process categorical spatial relations. As they admitted, however, it was not possible for them to test the specific prediction that the RVF-LH advantage would be reduced or eliminated, because no RVF-LH advantage was observed for the categorical task.[1] This prediction should be reexamined under conditions that would produce reliable visual field differences for spatial relation processing.

There are some methodological problems with blurring procedures. First, spatial frequencies are not accurately controlled. Cowin and Hellige (1994) did not provide any quantitative information about the spatial frequencies of the stimuli. It is not possible to tell exactly what range of frequencies was attenuated by blurring. Second, the disruptive effects of blurring can be explained in terms of discriminablity of the parts of the dot-and-bar stimuli (see Ivry & Robertson, 1998). The two parts positioned very closely (0.7 mm for the nearest distance) would have fused together when blurred. Such blurred stimuli would be difficult to judge as ''above'' or ''below'' on the categorical task. In contrast, they may easily be judged as ''near'' on the coordinate task. Third, the effects of blurring can be confounded with those of perceptual degradation. Various forms of perceptual degradation, including blurring, have been found to disrupt the performance on RVF-LH trials rather than on LVF-RH trials, and produce an LVF-RH advantage (see Sergent & Hellige, 1986; Sergent, 1983). If blurring should attenuate the performance on the RVF-LH trials rather than on the LVF-RH trials, this might have reflected the right hemisphere's relative resistance to perceptual degradation (Peterzell, Harvey, & Hardyck, 1989).

The present study investigated the role of high spatial frequency in the left hemispheric advantage for categorical spatial processing, while avoiding the methodological problems in Cowin and Hellige (1994). If high spatial frequency contributes to the processing of categorical spatial relations in the left hemisphere (Kosslyn et al., 1992), the RVF-LH advantage for the categorical task should be more reliable when the stimuli have higher spatial frequency content. Thus, the present experiment used the stimuli composed of small dots: These patterns have higher component frequencies than conventional dot-and-bar patterns because the stimulus elements are smaller. We previously reported a significant RVF-LH advantage for the categorical task using small dot stimuli (Okubo & Michimata, 2002). Digital spatial frequency filtering was used to directly and accurately control spatial frequencies. Unfiltered stimuli contained broadband spatial frequencies, whereas low-pass-filtered stimuli were devoid of high spatial frequencies (see Methods for details). The two parts were clearly discriminable because they were sufficiently separated so as not to fuse together when low-pass filtering was performed. It is known that frequency filters with abrupt cutoffs produce spurious ringing effects (i.e., filtered images are perceptually degraded). To minimize the degradation effects, the Gaussian envelope was used to perform low-pass filtering in the Fourier domain. In fact, there is little interference noise in the low-pass-filtered images (Figure 1B).

If the left hemisphere's efficiency for processing of high spatial frequency contributes to the left hemispheric advantage for processing categorical spatial relations, low-pass filtering will disrupt the performance on the categorical task in the RVF-LH trials and eliminate the RVF-LH advantage, whereas the filtering will not disrupt the LVF-RH advantage for the coordinate task.

RESULTS

For each participant, the percentage of errors and the median reaction time of correct responses were computed for each experimental condition. The results of the two measures were similar, with a high positive correlation ($r = .86$). Thus, there was no evidence of speed–accuracy tradeoff. Both error and reaction time data were subjected to a 2 (task: categorical vs. coordinate) × 2 (visual field: LVF-RH vs. RVF-LH) × 2 (filter: unfiltered vs. low-pass filtered) repeated measures analysis of variance.

Errors

Participants responded more accurately on the categorical task (3.78%) than on the coordinate task (7.04%), producing a significant main effect of task, $F(1,27) = 17.57$, $MSe = 32.11$, $p < .001$. Consistent with previous studies, there was a significant Task × Visual Field interaction, $F(1,27) = 4.50$, $MSe = 12.24$, $p = .04$. Responses for the categorical task were more accurate for the RVF-LH trials (3.42%) than for the LVF-RH trials (4.32%), whereas responses for the coordinate task were more accurate for the LVF-RH trials (6.50%) than for the RVF-LH trials (7.59%). A Task × Filter interaction was also significant, $F(1,27) = 7.06$, $MSe = 10.23$, $p = .008$. Responses for the categorical task were more accurate for the unfiltered stimuli (3.17%) than for the low-pass-filtered stimuli (4.56%). This closely replicated Cowin and Hellige's (1994) findings. On the other hand, responses for the coordinate task were more accurate for the low-pass-filtered stimuli (6.55%) than for the unfil-

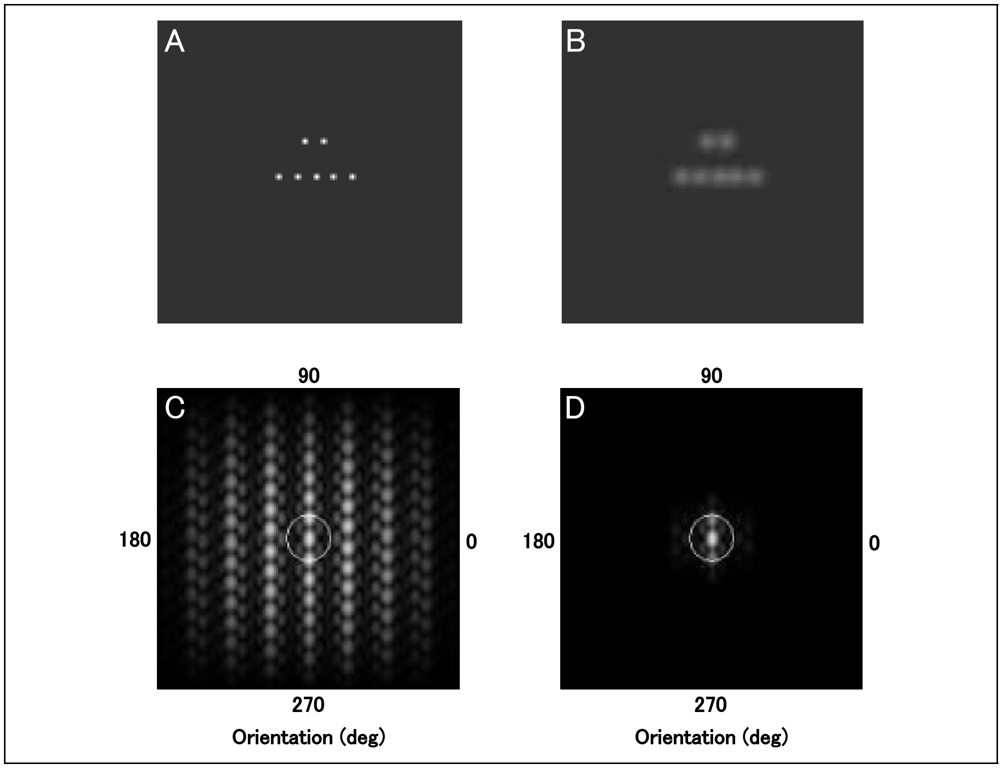

Figure 1. Examples and the Fourier transformations of representative stimuli used in the Experiment. A and B are the examples of the unfiltered and low-pass-filtered stimuli, respectively. C and D are the Fourier transformations of unfiltered and the low-pass-filtered stimuli, respectively. In C and D, the spatial frequency (cpd) corresponds to the distance from the center and orientation to the polar direction (degrees). The circles in C and D encompass frequencies below 5 cpd. The brightness represents the power of each frequency. The nearest distance stimuli were presented to show the discriminablity of the two parts of low-pass-filtered stimuli (B).

tered stimuli (7.54%). There was a significant Task × Visual Field × Filter interaction, $F(1,27) = 9.32$, $MSe = 21.35$, $p = .005$.

To clarify the effect of filtering on the visual field differences, a separate analysis was conducted for each filter condition. Figure 2 (left panel) shows the results for the unfiltered stimuli. Responses on the categorical task were significantly more accurate for the RVF-LH trials (1.78%) than for the LVF-RH trials (4.65%), $F(1,54) = 4.52$, $MSe = 23.85$, $p = .04$, whereas responses on the coordinate task were significantly more accurate for the LVF-RH trials (6.05%) than for the RVF-LH trials (9.03%), $F(1,54) = 5.19$, $MSe = 23.85$, $p = .03$.

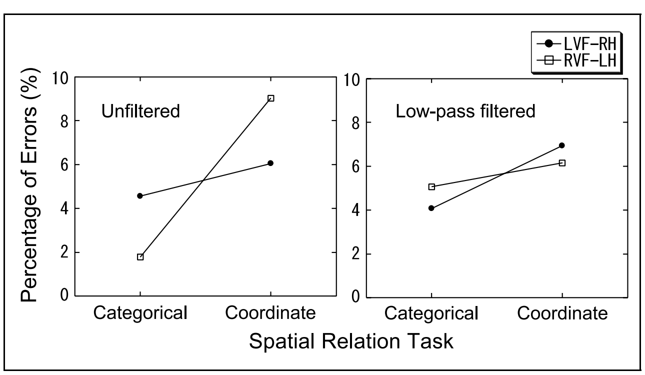

Figure 2. Mean percentage of errors on the LVF-RH and RVF-LH trials as a function of the spatial relation task. The results for the unfiltered and low-pass-filtered stimuli are presented in the left and right panels, respectively.

The Task × Visual Field interaction was significant, $F(1,27) = 9.71$, $MSe = 23.85$, $p = .004$. As is shown in the right panel of Figure 2, the patterns of visual field differences were reversed for the low-pass-filtered stimuli, and the Task × Visual Field interaction was not significant, $p = .14$. This shows that the RVF-LH advantage for the categorical task was eliminated.

We conducted a separate analysis for each visual field condition. The Task × Filter interaction was significant for the RVF-LH trials, $F(1,27) = 16.07$, $MSe = 16.48$, $p < .001$. Responses for the categorical task were more accurate for the unfiltered stimuli than for the low-pass-filtered stimuli, $F(1,54) = 9.10$, $MSe = 16.48$, $p = .003$. In contrast, responses for the coordinate task were more accurate for the low-pass-filtered stimuli than for the unfiltered stimuli, $F(1,54) = 7.03$, $MSe = 16.48$, $p = .01$. On the other hand, for the LVF-RH trials, neither a Task × Filter interaction, nor a main effect of filter was significant, $Fs < 1.00$. This shows that low-pass filtering selectively affected the RVF-LH trials.

Reaction Time

Figure 3 shows the results for reaction times.[2] The pattern of results was very similar to that of the error data. Participants responded faster on the categorical task (494 msec) than on the coordinate task (559 msec), producing a significant main effect of task, $F(1,27) = 29.62$, $MSe = 8099$, $p < .001$. Other main effects or interactions were not significant, $ps > .17$. However, as

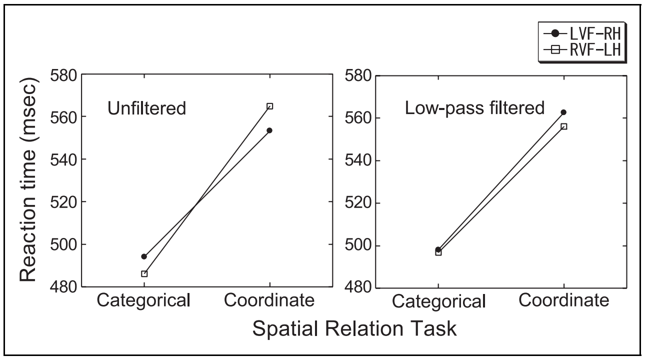

Figure 3. Mean median reaction time on the LVF-RH and RVF-LH trials as a function of the spatial relation task. The results for the unfiltered and low-pass-filtered stimuli are presented in the left and right panels, respectively.

was found for the error data, a separate analysis for the unfiltered stimuli revealed a significant Task × Visual Field interaction, in the direction that Kosslyn (1987) had predicted, $F(1,27) = 5.05$, $MSe = 530$, $p < .03$. On the other hand, the Task × Visual Field interaction was not significant for the low-pass-filtered stimuli, Fs $<$ 1.00; the disappearance of this interaction was also consistent with the error data.

DISCUSSION

The unfiltered condition resulted in a significant RVF-LH advantage for the categorical task and a significant LVF-RH advantage for the coordinate task. This closely replicated Okubo and Michimata (2002), which used the same stimuli composed of small dots. This finding of a Task × Visual Field interaction is important because there have been several failures to replicate this interaction (e.g., Wilkinson & Donnely, 1999; Cowin & Hellige, 1994; Sergent, 1991). In spite of these failures, the recent meta-analysis based on 16 experiments revealed that both the RVF-LH advantage for the categorical task and the LVF-RH advantage for the coordinate task were highly reliable, $p < .0001$ (Laeng et al., 2003). The results of this meta-analysis and the present study consistently suggest that hemispheric differences for spatial relation processing might be small in absolute terms, but they do exist.

Theoretically, the most important finding is that low-pass filtering eliminated this Task × Visual Field interaction, that is, low-pass filtering disrupted the categorical task in the RVF-LH trials and eliminated the RVF-LH advantage. These results directly support Kosslyn et al.'s (1992) hypothesis that the left hemisphere's efficiency for processing high spatial frequency contributes to the left hemispheric advantage for processing categorical spatial relations. Okubo and Michimata (2002) found that the LVF-RH advantage on the coordinate task disappeared in the absence of low spatial frequencies. Taken together, the present results strongly suggest that hemispheric processing of categorical and coordinate spatial relations depends on each hemisphere's ability to process spatial frequency.

In contrast to the present results, Cowin and Hellige (1994) reported that the effects of dioptic blurring did not differ between the RVF-LH and LVF-RH trials on the categorical task. However, their results were difficult to evaluate because they did not obtain any visual field differences on the categorical task and did not accurately control spatial frequencies. As was previously discussed, these methodological shortcomings may lead to problems (see also Ivry & Robertson, 1998; Christman, 1989). We believe that the problems were reasonably controlled in the present experiment. By use of the small dot stimuli, the reliable Task × Visual Field interaction was observed. Digital spatial filtering was used to overcome methodological shortcomings with blurring. Digital spatial filtering is one of the most desirable ways to directly and accurately manipulate spatial frequencies, especially when spectrally pure stimuli (i.e., sinusoidal gratings) are difficult to use.

The present experiment succeeded in controlling the discriminablity and perceptivity of the stimuli. This was supported by the fact that the participants' performance did not differ much between the two filter conditions. This finding is important not only methodologically but also theoretically. Peterzell et al. (1989) argued that the initial findings supporting the idea of hemispheric differences in the processing of spatial frequency (e.g., Sergent & Hellige, 1986) could be explained solely by perceptual degradation. However, the present experiment clearly demonstrated that, not perceptivity, but the manipulation of spatial frequency produced the substantial effects on the hemispheric processing of spatial relations. Thus, the present results are explained not by perceptivity, but rather by the spatial frequency content of the stimuli.

The simple dichotomy on hemispheric differences is always problematic (e.g., Bryden, 1982). The spatial frequency theory may not provide straightforward explanation on some results (e.g., Rebai, Bernard, Lannou, & Jouen, 1998; Boles & Rashid, 1993; Boles & Morelli, 1988). In addition, it has been showed that input variables (e.g., spatial frequency), relative to type of stimulus/processing variables (e.g., word vs. figure), may have a smaller effect on visual field differences (e.g., Boles, 1994). However, the present results directly support the spatial frequency theory and strongly suggests that spatial frequencies play a significant role at least in hemispheric processing of spatial relations.

The effects of low-pass filtering were restricted to the RVF-LH trials and were disruptive for the categorical task and facilitative for the coordinate task. The disruptive effects on the categorical task are consistent with our hypothesis. The facilitative effects on the coordinate task may be difficult to interpret. One possibility is that the left hemisphere's disadvantage of coordinate relations might be balanced when the available input is highly appropriate for coordinate processing. Although there would be a relative hemispheric difference in processing spatial frequencies, both hemispheres are capable of processing high and low spatial frequencies (e.g., Fendrich & Gazzaniga, 1990). Thus, the left hemisphere may process coordinate spatial relations as efficiently as the right hemisphere for the low-pass-filtered stimuli, which are known to be appropriate for coordinate processing (Baker et al., 1999; Jacobs & Kosslyn, 1994; Kosslyn et al., 1992).

Recent computational theories of hemispheric differences in visual information processing place great importance on each hemisphere's ability to process spatial frequencies (e.g., Ivry & Robertson, 1998; Kosslyn et al., 1992). The present results support these theories and suggest that there is a direct link between the processing of high spatial frequency and categorical spatial relations in the left cerebral hemisphere. It has been reported that categorical and coordinate spatial relations play an important role in basic-level object recognition and face recognition, respectively (e.g., Cooper & Wojan, 2000), and in hemispheric differences in object recognition (Laeng et al., 1999). Together with our previous findings (Okubo & Michimata, 2002), the present results may ultimately suggest the possibility that processing of spatial frequency may contribute to hemispheric asymmetries for high-level visual processes through the intermediary of processing categorical and coordinate spatial relations.

METHODS

Participants

Participants were 28 college students (18 women, 10 men). 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 (filter: unfiltered vs. low-pass filtered) factorial design. All variables were manipulated within participants. The dependent variables were errors and reaction time.

Apparatus

An Apple high-resolution monochrome monitor and Apple Power Macintosh G3 MT233 were used for the presentation and generation of the stimuli and for recording participants' responses. The monitor was gamma-corrected using the ISR video attenuator (Pelli & Zhang, 1991). A 10-key pad (Sanwa Supply NT-MAC 2) was connected to the computer and served as a 4-key response console. The experiment was controlled by Matlab with Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997).

Stimuli

Figure 1 shows an example of the unfiltered and low-pass-filtered stimuli. The unfiltered stimuli were composed of seven dots. The size of each dot was 4 × 4 min of arc. The luminance was 58 cd/m^2 for each dot and was 19 cd/m^2 for the background. A row of five dots served as the reference (i.e., the bar in the dot-and-bar stimuli). The horizontal separation between the dots was set to 0.2° of visual angle. The reference subtended approximately 1.3°. Two dots were also aligned horizontally and served as the target. They were located in 1 of the 12 possible positions with respect to the reference, subtending 0.5°, 1.0°, 1.5°, 2.5°, 3.0°, and 3.5° above or below the reference.

Low-pass-filtered images were created by computing Fourier transformations of the unfiltered image, convolving the output by the use of the filter with 2-D Gaussian envelope (σ = 3 cpd), and computing the inverse transforms. The Gaussian filter was used to avoid spurious ringing effects. The power of the spatial frequency gradually decreased as the number of the frequency increased and disappeared around 5 cpd. The representative patterns of Fourier transformations of the unfiltered and the low-pass-filtered stimuli are shown in Figure 1C and D, respectively. The cutoff frequency was determined based on our previous finding that the RVF-LH advantage was intact for the categorical task when frequencies below 3 cpd were removed (Okubo & Michimata, 2002). This may imply that frequencies above 3 cpd were responsible for the RVF-LH advantage for the categorical task.

The fixation dot was positioned at the center of the display. Each stimulus pattern was presented to either the right or the left visual field. The centermost dot of each pattern was 2° away from the fixation. The vertical position of the reference was the same as the fixation.

Procedure

At the beginning of the experiment, participants adapted to the mean luminance of the display for 10 min. They were told to keep the index and middle fingers of their left and right hands 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 that 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 on a chin rest. Each trial began with the onset of the fixation for 750 msec, followed immediately by the stimulus pattern for 150 msec. Participants made their responses on simultaneously pressing two keys with their index or middle fingers. The finger-response mapping was counterbalanced across participants.

All participants performed the categorical task first, followed by the coordinate task.[3] Before the categorical task, participants received four practice trials. No practice trial was given for the coordinate task. For the categorical task, participants indicated whether the target was above or below the reference, with the distance between the dots being irrelevant. For the coordinate task, participants indicated whether the target was within 2 cm of the reference.

Participants received a total of 288 trials, which were divided into 6 blocks of 48 trials consisting of an orthogonal combination of the 12 possible dot positions, 2 visual fields, and 2 filter conditions. The stimuli were presented to participants in different random orders: The visual fields and the filter conditions were randomly changed for each trial. Participants received a short break after each trial block.

Acknowledgments

This research was supported by the Japan Society for the Promotion of Science and a grant from the Ministry of Education, Culture, Sports, Science, and Technology of Japan to the first author.

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Notes

1. It is possible that removing high spatial frequencies through blurring shifts the visual field difference toward the left visual field even if no overall right field advantage is found. However, the test of the prediction may be more optimal on the condition that produces the reliable visual field difference than on the condition that does not.
2. The median reaction time was very fast in the present experiment. The reason for the fast reaction time is not very clear. However, we are confident that the faster responses were not made at the expense of accuracy. The error rate was relatively small and there was no evidence of speed–accuracy tradeoff in the present experiment. Therefore, the faster reaction time may not have negative effects on the present results.
3. 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 4-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 to become familiar with the response procedure and the experimental settings without performing the coordinate task.

REFERENCES

Baker, D. P., Chabris, C. F., & Kosslyn, S. M. (1999). Encoding categorical and coordinate spatial relations without input–output correlations: New simulation models. *Cognitive Science, 23,* 33–51.

Boles, D. (1994). An experimental comparison of stimulus type, display type, and input variable contributions to visual field asymmetry. *Brain and Cognition, 24,* 184–197.

Boles, D., & Morelli, M. (1988). Hemispheric sensitivity to spatial frequencies. *Bulletin of the Psychonomic Society, 26,* 552–555.

Boles, D., & Rashid, R. (1993). Spatial frequency masking of lateralized word recognition. *Bulletin of the Psychonomic Society, 31,* 563–565.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10,* 433–436.

Bryden, M. P. (1982). *Laterality: Functional asymmetry in the intact brain.* New York: Academic Press.

Christman, S. (1989). Perceptual characteristics in visual laterality research. *Brain and Cognition, 11,* 238–257.

Cooper, E. E., & Wojan, T. J. (2000). Differences in the coding of spatial relations in face identification and basic-level object recognition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26,* 470–488.

Cowin, E. L., & Hellige, J. B. (1994). Categorical versus coordinate spatial processing: Effects of blurring and hemispheric asymmetry. *Journal of Cognitive Neuroscience, 6,* 156–164.

Fendrich, R., & Gazzaniga, M. (1990). Hemispheric processing of spatial frequencies in two commissurotomy patients. *Neuropsychologia, 28,* 657–663.

Grabowska, A., & Nowicka, A. (1996). Visual–spatial-frequency model of cerebral asymmetry: A critical survey of behavioral and electrophysiological studies. *Psychological Bulletin, 120,* 434–449.

Hellige, J. B., & Michimata, C. (1989). Categorization versus distance: Hemispheric differences for processing of spatial information. *Memory and Cognition, 17,* 770–776.

Ivry, R. B., & Robertson, L. C. (1998). *The two sides of perception.* Cambridge: MIT Press.

Jacobs, R. A., & Kosslyn, S. M. (1994). Encoding shape and spatial relations: The role of receptive field size in coordinating complementary representations. *Cognitive Science, 18,* 361–386.

Jager, G., & Postma, A. (2003). On the hemispheric specialization for categorical and coordinate spatial relations: A review of the current evidence. *Neuropsychologia, 41,* 504–515.

Kitterle, F. L., Christman, S., & Hellige, J. B. (1990). Hemispheric differences are found in the identification, but not the detection, of low versus high spatial frequencies. *Perception and Psychophysics, 48,* 297–306.

Kitterle, F. L., Hellige, J. B., & Christman, S. (1992). Visual hemispheric asymmetries depend on which spatial frequencies are task relevant. *Brain and Cognition, 20,* 308–314.

Kitterle, F. L., & Selig, L. M. (1991). Visual field effects in the discrimination of sine-wave gratings. *Perception and Psychophysics, 50,* 15–18.

Kosslyn, S. M. (1987). Seeing and imaging in the cerebral hemispheres: A computational approach. *Psychological Review, 94,* 148–175.

Kosslyn, S. M. (1994). *Image and brain.* Cambridge: MIT Press.

Kosslyn, S. M., Chabris, C. E., Marsolek, C. J., & Koenig, O. (1992). Categorical versus coordinate spatial relations: Computational analyses and computer simulation. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 562–575.

Kosslyn, S. M., Koenig, O., Barrett, A., Cave, C. B., Tang, J., & Gabrieli, J. D. E. (1989). Evidence for two types of spatial relations: Hemispheric specialization for categorical and coordinate relation. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 723–735.

Laeng, B., Chabris, C. F., & Kosslyn, S. M. (2003). Asymmetries in encoding spatial relations. In K. Hugdahl & R. J. Davidson (Eds.), *The asymmetrical brain* (pp. 303–339). Cambridge: MIT Press.

Laeng, B., Shah, J., & Kosslyn, S. M. (1999). Identifying objects in conventional and contorted poses: Contributions of hemispheric-specific mechanisms. *Cognition, 70,* 53–85.

Michimata, C. (1997). Hemispheric processing of categorical and coordinate spatial relations in vision and visual imagery. *Brain and Cognition, 33,* 370–387.

Okubo, M., & Michimata, C. (2002). Hemispheric processing of categorical and coordinate spatial relations in the absence of low spatial frequencies. *Journal of Cognitive Neuroscience, 14,* 291–297.

Pelli, D. G. (1997). The videotoolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10,* 437–442.

Pelli, D. G., & Zhang, L. (1991). Accurate control of contrast on microcomputer displays. *Vision Research, 31,* 1337–1350.

Peterzell, D. H., Harvey, J. R., & Hardyck, C. D. (1989). Spatial frequencies and the cerebral hemispheres: Contrast sensitivity, visible persistence, and letter classification. *Perception and Psychophysics, 46,* 443–455.

Rebai, M., Bernard, C., Lannou, J., & Jouen, F. (1998). Spatial frequency and right hemisphere: An electrophysiological investigation. *Brain and Cognition, 36,* 21–29.

Rybash, J. M., & Hoyer, W. J. (1992). Hemispheric specialization for categorical and coordinate spatial representations: A reappraisal. *Memory and Cognition, 20,* 271–276.

Sergent, J. (1982). The cerebral balance of power: Confrontation or cooperation? *Journal of Experimental Psychology: Human Perception and Performance, 8,* 253–272.

Sergent, J. (1983). The role of input in visual hemispheric asymmetries. *Psychological Bulletin, 93,* 481–514.

Sergent, J. (1991). Judgments of relative position and distance on representation of spatial relations. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 762–780.

Sergent, J., & Hellige, J. B. (1986). Role of input factors in visual field asymmetries. *Brain and Cognition, 5,* 174–199.

Wilkinson, D., & Donnely, N. (1999). The role of stimulus factors in making categorical and coordinate spatial judgments. *Brain and Cognition, 39,* 171–185.