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Individual Variation in Hemispheric Asymmetry: Multitask Study of Effects Related to Handedness and Sex

Joseph B. Hellige, Michael I. Bloch, Elizabeth L. Cowin, Tami Lee Eng,
Zohar Eviatar, and Vicki Sergent

Functional hemispheric asymmetries were examined for right- or left-handed men and women. Tasks involved (a) auditory processing of verbal material, (b) processing of emotions shown on faces, (c) processing of visual categorical and coordinate spatial relations, and (d) visual processing of verbal material. Similar performance asymmetries were found for the right-handed and left-handed groups, but the average asymmetries tended to be smaller for the left-handed group. For the most part, measures of performance asymmetry obtained from the different tasks did not correlate with each other, suggesting that individual subjects cannot be simply characterized as strongly or weakly lateralized. However, ear differences obtained in Task 1 did correlate significantly with certain visual field differences obtained in Task 4, suggesting that both tasks are sensitive to hemispheric asymmetry in similar phonetic or language-related processes.

The purpose of the present research was to investigate individual variation in aspects of cerebral hemisphere asymmetry and in the pattern of interaction between the cerebral hemispheres. Individuals have been hypothesized to differ along a number of dimensions of cerebral hemisphere asymmetry, including the direction and magnitude of hemispheric superiorities for specific processes, the direction and magnitude of arousal differences between the hemispheres, and various aspects of interhemispheric communication and coordination. Individual variation in cerebral hemisphere asymmetry has also been hypothesized to be related to handedness and to the sex of the subject. In the present research, the same groups of right- or left-handed men and women participated in four experiments designed to tap different aspects of functional hemispheric asymmetry. This permitted further examination of effects related to handedness and to the sex of the subject. In addition, because the same individuals participated in all four experiments, it was possible to examine the extent to which hemispheric asymmetry for one task was related to hemispheric asymmetry for the other tasks. Because the different tasks made different information-processing demands, the pattern of intercorrelations sheds light on the mechanisms responsible for individual variation.

Each of the present experiments was motivated by theoretical predictions and previous findings having to do with specific aspects of hemispheric asymmetry. In view of this, the motivation behind the use of the various tasks will be described in the introduction to each experiment. For the moment, however, it is useful to note that Experiment 1 involved a verbal dichotic listening task, Experiment 2 involved the processing of emotion shown on faces in a free-vision task, Experiment 3 involved tachistoscopic tasks that examine hemispheric asymmetry for two aspects of spatial processing, and Experiment 4 involved the identification of tachistoscopically presented nonsense syllables. After the general methods and order of testing are described, each of the experiments is presented and discussed with respect to its implications about the relevant aspects of hemispheric asymmetry.

Even though each of the experiments was motivated by unique theoretical issues, it is instructive to point out certain purposes that were common to all of them. For example, with respect to handedness, it has generally been reported that patterns of asymmetry are similar for groups of right- and left-handers, but the mean asymmetries often are smaller for the left-handed group than for the right-handed group. When this occurs, it is often because the direction of asymmetry is more variable within the group of left-handers, not because the magnitude of asymmetry (regardless of direction) is smaller for left-handed individuals (for examples and reviews, see Bradshaw, 1989; Bryden, 1982; Bryden & Steenhuis, 1991; Coren, 1990, 1992; Hellige, 1993a, 1994; Levy, Heller, Banich, & Burton, 1983b; McKeever, 1991). Therefore, one common purpose of the present experiments was to provide additional information about these effects related to handedness and to examine their consistency across experimental tasks.

With respect to the sex of the subject, both theoretical predictions and previous findings have been quite variable. For example, at various times it has been argued that hemispheric asymmetry is more pronounced for men than for

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Joseph B. Hellige, Michael I. Bloch, Elizabeth L. Cowin, Tami Lee Eng, Zohar Eviatar, and Vicki Sergent, Department of Psychology, University of Southern California.

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Correspondence concerning this article should be addressed to Joseph B. Hellige, Department of Psychology, University of Southern California, Los Angeles, California 90089-1061.

women, that hemispheric asymmetry is less pronounced for men than for women, and that asymmetries do not differ for men and women (for examples and reviews, see Bradshaw, 1989; Bryden, 1982; Hellige, 1993a; Hiscock, Hiscock, & Inch, 1991, 1992; Hiscock, Hiscock, & Kalil, 1990). On balance, there is not much evidence in favor of consistent sex differences in either direction, especially when such things as handedness and processing strategy are controlled. Nevertheless, a second common purpose of the present experiments was to provide additional investigation of possible differences in hemispheric asymmetry related to the sex of the subject. It has also been suggested that handedness and subjects' sex interact in potentially complex ways to influence both functional and biological aspects of hemispheric asymmetry, so that effects of subjects' sex may be different for left-handers than for right-handers for some tasks but not for others (e.g., Galaburda, Rosen, & Sherman, 1990; Harshman & Hampson, 1987; Hellige, 1993a; McKeever, 1986; Witelson & Nowakowski, 1991). If such interactions exist, they can be observed only by including both variables in the same set of experiments.

After each of the experiments has been presented and discussed, we examine the extent to which the aspects of hemispheric asymmetry and interhemispheric interaction measured by the different tasks are related to each other. The theoretical rationale for expecting certain relationships will be developed throughout presentation of the individual experiments. It is worth noting at the outset, however, that one rationale for including left-handers in studies of this kind is that the range of individual differences in asymmetry is likely to be greater when left-handers are included. This greater range may make it easier to discover interesting relationships among the tasks (e.g., Hines & Satz, 1974). There have also been hypotheses about certain aspects of hemispheric asymmetry being different for people who have left-handed relatives [i.e., those with familial sinistrality (FS+)] than for people who do not [i.e., those without familial sinistrality (FS−; e.g., Hécaen, De Agostini, & Monzon-Montes, 1981; Krutsch & McKeever, 1990)]. For this reason, we selected the sample such that approximately half of the left-handers had at least one other left-hander in their immediate family, and the remainder did not.

The Experiments: General Method

Subjects

Participants in the present experiments were volunteers from introductory psychology classes at the University of Southern California. All were native speakers of English who had no known hearing impairments and who had normal or corrected-to-normal vision in both eyes. Each participant completed a modified version of the Edinburgh Handedness Inventory (Oldfield, 1971) and was classified according to which hand he or she normally used for writing and drawing. All participants reported very strong hand preferences for these two activities, and no participant preferred one hand for writing but the other hand for drawing. This procedure resulted in a total of 56 right-handers (26 men and 30 women) and 63 left-handers (30 men and 33 women). Two of the right-handers (1 man and 1 woman) and 32 of the left-handers (17 men and 15 women) reported having at least 1 left-handed sibling or parent (i.e., FS+), whereas the other subjects reported having only right-handed siblings and parents (FS−). For various reasons that were unrelated to subjects' handedness or performance (e.g., equipment problems), data from one task or another could not be used for some subjects. The strategy we adopted was to analyze data for each task for all of the subjects for whom data on that task were complete.

Order of Tasks

Each subject performed five experimental tasks spread across two test sessions, with the sessions being approximately 1 week apart. All subjects were tested in the same order so that individual differences on the various tasks could not be attributed to different opportunities for order and carryover effects. During the first session, subjects performed (in order) the Above–Below spatial processing task, the dichotic-listening task, and the free-vision face task. During the second session, subjects performed (in order) the consonant–vowel–consonant (CVC) syllable identification task and the Near–Far spatial processing task. At the end of the second session, subjects completed a handedness questionnaire. For convenience of exposition, the methods and results of each of the four experiments will be described together in turn. This will be followed by a description of the interrelations among tasks that come from the different experiments. The order of presentation of the four experiments is arbitrary.

Experiment 1: Dichotic Listening

In Experiment 1, subjects performed a dichotic listening task identical to that used by Hellige, Bloch, and Taylor (1988). On each trial, a different consonant–vowel (CV) syllable was presented to each ear, and subjects attempted to choose both syllables from a set of 6 alternatives. This task was chosen for the following reasons.

Various dichotic listening tasks similar to the one used here have been used a great deal in studies of perceptual asymmetry—including studies of the effects related to handedness and to subjects' sex. Consequently, one reason for including the task is to check that the samples of right- or left-handed men and women used in the present study are similar to samples studied by other investigators. On the basis of previous studies, both the right- and left-handed groups are expected to recognize more CVs from the right ear than from the left ear, a perceptual asymmetry that is related to the fact that the left hemisphere is generally superior to the right hemisphere for phonetic processing (e.g., Hellige, Bloch, & Taylor, 1988; Hugdahl, 1988; Porter & Hughes, 1983; Zaidel, 1983). In addition, the extent to which there is a right-ear advantage for recognizing verbal stimuli is often (though not always) less for left-handers than for right-handers. This can often be seen in a reduced mean right-ear advantage for the left-handed group compared with the right-handed group, in a smaller proportion of left-handers (relative to right-handers) who show a difference in favor of the right ear, or both (e.g., Bryden, 1982; Dagenbach, 1986; Hellige, 1993a; Hines & Satz, 1974; Krutsch & McKeever, 1990; McKeever, 1986). Although there have been occasional reports that the magnitude of the right-ear advantage differs for men and women, the predominant finding has been that there is no such effect related to subjects' sex (e.g., Hiscock et al., 1990).

This specific dichotic listening task was also chosen because Hellige, Bloch, and Taylor (1988) used it in a previous multitask investigation of individual differences in hemispheric asymmetry among right-handers and showed it to be related to the pattern of lateralized interference in a dual-task finger tapping paradigm. Among other things, this argues against the possibility that all of the individual variation in ear asymmetry reflects such things as variation in asymmetry of the auditory projection pathways or other variables that are unique to the auditory modality.

In the dual-task portion of the study reported by Hellige, Bloch, and Taylor (1988), right-handers were required to tap a microswitch with the index finger of their right or left hand as quickly as possible while doing nothing else or while performing one of two concurrent tasks. One concurrent task was repeating CV syllables aloud and the other was solving anagrams. For right-handers, both of these concurrent verbal tasks slowed the tapping rate of the right hand more than the tapping rate of the left hand, a result that has been attributed to the fact that the concurrent verbal tasks require more resources from the left hemisphere than from the right hemisphere (for discussion, see Cherry & Kee, 1991; Hellige & Kee, 1990; Kee, Hellige, & Bathurst, 1983; Kinsbourne & Hiscock, 1983; V. Sergent, Hellige, & Cherry, 1993). Hellige, Bloch, and Taylor (1988) replicated this effect and found that this asymmetric manual interference was correlated with the ear difference in dichotic listening. As the right ear advantage increased, the tendency for concurrent verbal processing to interfere more with right-hand tapping than with left-hand tapping was greater (suggesting a greater tendency to rely selectively on processing resources of the left hemisphere during the reading task.) In fact, for a small group of right-handers who showed a left-ear advantage during the dichotic listening task, repeating CV syllables aloud interfered more with left-hand tapping than with right-hand tapping, and solving anagrams interfered equally with the performance of both hands.

Hellige, Bloch, and Taylor (1988) also found that neither ear asymmetry on the dichotic listening task nor asymmetric interference in the dual-task paradigm was related to performance asymmetry on a free-vision face task involving judgments of emotion (a task for which the right hemisphere is thought to be more involved, and which is used in the present Experiment 2) or to performance on a task that required subjects to identify a printed CV presented tachistoscopically to either the left visual field/right hemisphere (LVF/RH) or right visual field/left hemisphere (RVF/LH) on each trial (a task that did not produce any visual field asymmetry). This entire pattern of results suggests that at least some of the individual variation in ear asymmetry on the dichotic listening task is related to hemispheric dominance for certain aspects of phonetic processing but not to the variables that produce individual variation in the asymmetry found for these other less verbal visual tasks. As we discuss in more detail later, one purpose of the present research was to explore these possibilities more fully by examining the relationship of ear asymmetry to various asymmetries obtained for a variety of additional visual tasks.

Method

Apparatus and stimulus materials. The apparatus and stimulus materials were identical to those used by Hellige, Bloch, and Taylor (1988). The auditory stimuli were the six CV syllables /ba/, /da/, /ga/, /pa/, /ta/, and /ka/. They were prepared from natural speech samples so that the onsets of the two stimuli within a pair were simultaneous within 2.5 ms and so that the amplitudes of the vowel segments were within 2.5 dB of each other. Each of the 30 possible pairs of different CV syllables was presented once in each of four different 30-trial sets. The order of pairs within each 30-trial set was random, with the restriction that no specific CV syllable occurred on more than 3 successive trials. The interval between the onsets of successive pairs within a set was approximately 6 s. The CV stimuli were presented to subjects over Koss Pro 4AAA stereo headphones connected to the headphone output jack of a TEAC Model A2300D reel-to-reel tape deck. The stimuli were presented at an intensity of approximately 75dB per channel, as measured from a calibration tone with a GenRad Type 1551–C Sound Level Meter using the B weighting.

Procedure. Subjects were instructed to try to identify both of the CV syllables presented on each trial. Although subjects were told that two CV syllables would be presented simultaneously on each trial, no mention was made of the fact that each CV would be presented to only one ear. For each 30-trial set, subjects made their responses on a response sheet with the trials numbered from 1 to 30. All six CV syllables were listed for each trial, and subjects were told to cross out two of the six alternatives as their best guesses about which two stimuli had been presented. Subjects were given all four 30-trial sets, with a break of approximately 30 s between successive sets. Before these experimental trials, subjects were given 20 practice trials with only one CV per trial. The single CV was presented to only one ear, with 10 CVs per ear. The response procedure was the same as that used on experimental trials except that only one response was made per trial.

Results and Discussion

Right-handers. Dichotic listening performance was available for all 56 right-handers. We conducted an analysis of variance (ANOVA) with sex of the subject as a between-subjects variable and ear of stimulus presentation as a within-subjects variable. The dependent variable was the number of stimuli recognized from each ear (from a maximum of 120 for each ear). As we expected from previous research, significantly more CV stimuli were recognized from the right ear (74.1%) than from the left ear (65.6%),

$F(1, 54) = 30.83$, $MS_e = 97.00$, $p < .001$. No other effects were statistically significant.

Left-handers. Dichotic listening performance was available for all 63 left-handers. We conducted an ANOVA that included sex of the subject and presence versus absence of familial sinistrality as between-subjects variables and ear of stimulus presentation as the within-subjects variable. Significantly more CV stimuli were again recognized from the right ear (69.6%) than from the left ear (64.0%), $F(1, 59) = 9.44$, $MS_e = 151.86$, $p < .005$. No other effects were statistically significant in this analysis. In an ANOVA that included handedness as a between-subjects variable, the overall percentage of correct CV identifications was significantly higher for right-handers (69.9%) than for left-handers (66.8%), $F(1, 115) = 4.58$, $MS_e = 182.60$, $p < .05$. Planned comparisons indicated that this effect of handedness was restricted to the identification of stimuli presented to the right ear. Despite this, however, the Handedness × Ear interaction was not statistically significant, $F(1, 115) = 1.65$.

Table 1 shows the number of right- and left-handers who recognized more CV stimuli from their right or left ear. Although the proportion of left-handers who showed a right-ear (left-hemisphere) advantage was somewhat smaller than the proportion of right-handers who showed such an advantage, this difference between right- and left-handers was not statistically significant, χ^2 (1, $N = 114) = 1.91$.

The pattern of results obtained in Experiment 1 is consistent with expectations derived from previous studies using similar dichotic listening paradigms with linguistic stimuli. Thus, with respect to hemispheric asymmetry for auditory–linguistic processing, the samples of right- or left-handed men and women used in the present study seem similar to samples that have been studied by other investigators. The results are also consistent with the majority of previous studies in that they show no effects of subjects' sex or of familial sinistrality.

Experiment 2: Processing of Faces and Emotions in Free Vision

In Experiment 2 we used a free-vision face task developed by Levy, Heller, Banich, and Burton (1983a, 1983b): On each trial, the subject is shown two faces, one above the other, and must indicate which of the two looks happier. Each face consists of a chimera constructed from the same poser, photographed once with a neutral expression and once with a happy expression. The two faces shown on a trial are mirror images of each other so that they differ only with respect to whether the happy expression is toward the viewer's right or toward the viewer's left. For this type of free-vision face-processing task, right-handers typically have a strong bias to report that the face with the happy expression on the viewer's left looks happier than its mirror image (e.g., Best, Womer, & Queen, 1994; Christman & Hackworth, 1993; Hellige, Bloch, & Taylor, 1988; Levy et al., 1983a, 1983b; Luh, Rueckert, & Levy, 1991). As a group, left-handers also tend to show a bias in the same direction, although the bias is smaller than the one shown by right-handers (e.g., Levy et al., 1983b). Levy et al. hypothesized that the left-side bias for this task is related to right hemisphere involvement in the processing of faces and emotions (see also Best et al., 1994; Christman & Hackworth, 1993; Luh et al., 1991). Levy et al. also suggested that at least some of the individual variation in this type of asymmetry is related to the fact that individuals differ in their characteristic and habitual patterns of asymmetric hemispheric arousal, which serves to magnify or counteract perceptual asymmetries arising from hemispheric dominance (see also Hellige, Bloch, & Taylor, 1988; Kim & Levine, 1991; Kim, Levine, & Kertesz, 1990; Levine, Banich, & Kim, 1987; Levine, Banich, & Koch-Weser, 1984; Levy, 1983).

We chose the free-vision face task for the present research because, like the dichotic listening task, it has been used in previous research with both right- and left-handers and with men and women. Consequently, it can be used to determine the extent to which the present samples are similar to the samples studied by other investigators. In addition, its use in previous multitask studies of individual differences (e.g., Hellige, Bloch, & Taylor, 1988) provides a point of contact between those earlier studies and the present research. Furthermore, to the extent that individual variation on the free-vision face task is related to variation in the direction and magnitude of hemispheric dominance for the processing of faces and emotions and to the direction and magnitude of characteristic arousal asymmetry, performance on the face-processing task should be related to other measures of asymmetry that are also influenced by either of those variables.

Table 1
Number of Subjects With Right- or Left-Ear Dominance for CV Recognition

Handedness	Dominant ear Left (Right hemisphere)	Right (Left hemisphere)
Right	9	45
Left	17	45

Note. CV = consonant–vowel. Two right-handers and 1 left-hander recognized an equal number of stimuli from both ears.

Method

Stimulus materials. The stimulus materials were identical to those used by Levy et al. (1983b). Each of 9 men was photographed once with an emotionally neutral expression and once with a happy expression. From these, 36 pairs of chimeric faces were constructed in the following manner. The two halves of each chimeric face came from the same individual, but each half displayed a different expression. That is, one side of each chimeric face showed a neutral expression and the other side showed a happy expression. The two chimeric faces in each pair were photographic mirror images of each other and were presented one above the other on 21.5-cm × 35-cm cards. That is, the two faces on each card were identical except for the side on which the happy expression was presented. Photographs of each of the 9 individuals were used to generate 4 such cards. On 2 of the cards the happy expression came from the left side of the individual's face, and on 2 cards the happy expression came from the right side of the individual's face (with the neutral expression coming from the opposite side). Orthogonal to this, on 2 cards the normal photographic print was presented at the top of the card and the mirror image was at the bottom, and on the other 2 cards this was reversed. The 36 stimuli were administered to each subject in the order used by Levy et al. and by Hellige, Bloch, and Taylor (1988).

Procedure. The experimenter presented 1 card at a time on a typing stand directly in front of the subject's midline. For each card, subjects indicated whether the top face or bottom face looked happier by circling their choice on a response sheet.

Results and Discussion

We obtained a bias score from each subject using the formula $(R - L)/36$, where R is the number of trials on which the face with the smile on the viewer's right was judged to look happier, and L is the number of trials on which the face with the smile on the viewer's left was judged to look happier. Thus, a positive score indicates a bias toward the right side of space, and a negative score indicates a bias toward the left side of space.

Right-handers. Performance on the free-vision face task was available for all 56 right-handers. For this group, the mean bias score was −0.350, which was significantly less than 0, $t(55) = -5.38, p < .001$. An ANOVA indicated that the bias score for right-handers was not influenced significantly by subjects' sex.

Left-handers. Performance on the free-vision face task was available for 62 left-handers (29 men and 33 women). For this group, the mean bias score was −0.119, with the difference from 0 approaching statistical significance, $t(61) = -1.73, .05 < p < .10$. An ANOVA indicated that the bias score for left-handers was not significantly influenced by subjects' sex or by the presence versus absence of familial sinistrality. An ANOVA that included handedness as a between-subjects variable indicated that the mean bias score was significantly smaller for right-handers than for left-handers, $F(1, 114) = 6.08, MS_e = 0.269, p < .025$.

Table 2 shows the number of right- and left-handers whose face-processing bias scores suggested left- versus right-hemisphere dominance. Compared with right-handers, there were significantly fewer left-handers with right-hemisphere dominance and more left-handers with left-hemisphere dominance, $\chi^2\ (1, N = 114) = 5.70, p < .025$.

Table 2
Number of Subjects With Right- or Left-Hemisphere Dominance for the Face-Processing Task

Handedness	Dominant hemisphere Right	Left
Right	42	12
Left	34	26

Note. Two right-handers and 2 left-handers showed no bias.

The results of Experiment 2 are consistent with the results of previous experiments and provide a further indication that the samples used in the present experiments are similar to samples used by previous investigators. Specifically, the fact that most subjects were biased toward the left side of the face (from the viewer's perspective) is consistent with the results of several previous studies, as is the absence of differences related to the sex of the subject. Our finding that the leftward bias was smaller for left-handers than for right-handers also replicates a similar finding reported by Levy et al. (1983b). In addition, the results of Experiment 2 indicate that bias on the face-processing task is not related to the presence versus absence of familial sinistrality.

Experiment 3: Spatial Processing and Hemispheric Asymmetry

In Experiment 3 we used two tasks developed by Hellige and Michimata (1989) to study hemispheric asymmetry for processing different types of spatial information. On each trial, subjects were presented with a stimulus consisting of a horizontal line and a small dot in one of 12 possible locations (6 above the line and 6 below the line). On different trials, stimuli were presented briefly to the LVF/RH, to the RVF/LH, or the same stimulus was presented to both visual fields (and hemispheres) simultaneously (redundant bilateral trials). During different experimental sessions, each subject performed two tasks using these stimuli. One task, the Above–Below task, required subjects to indicate whether the dot on each trial was above or below the line, ignoring the distance between the dot and the line. The other task, the Near–Far task, required subjects to indicate whether or not the dot on each trial was within 2 cm of the line.

Kosslyn and his colleagues have hypothesized that our brains compute two kinds of spatial-relation representations (e.g., Kosslyn, 1987; Kosslyn, Chabris, Marsolek, & Koenig, 1992; Kosslyn, Flynn, Amsterdam, & Wang, 1990; Kosslyn et al., 1989). One type is used to assign a spatial relation to a category such as "above" or "below," and the other type is used to preserve precise information about distance using a kind of metric coordinate system. Kosslyn (1987) hypothesized that so-called categorical spatial information (tapped by the Above–Below task) is computed more effectively by the left hemisphere, whereas so-called coordinate or distance information is computed more effectively by the right hemisphere. Hellige and Michimata (1989) developed the Above–Below and Near–Far tasks to test these ideas, and their results provide at least partial support. That is, in their experiment with right-handed subjects, there was a significant Task × Visual Field interaction consisting of a significant LVF/RH advantage for the Near–Far task and a nonsignificant trend toward a RVF/LH advantage for the Above–Below task. Results similar to this have now been reported in subsequent experiments, all with right-handed subjects (e.g., Koenig, Reiss, & Kosslyn, 1990; Kosslyn et al., 1989; Rybash & Hoyer, 1992). The Above–Below and Near–Far tasks were included in the present series of experiments for the following reasons.

Despite the fact that the critical Task × Visual Field interaction has now been obtained in several experiments, the effects are generally quite small. In fact, the predicted RVF/LH advantage for the Above–Below task is almost never statistically significant, and the LVF/RH advantage for the Near–Far task sometimes disappears with practice (e.g., Cowin & Hellige, 1994; Kosslyn et al., 1989; Rybash & Hoyer, 1992; see also J. Sergent, 1991). This being the case, an additional attempt to replicate the results for right-handers seemed worthwhile. In addition, using other categorical and coordinate tasks, Kosslyn (1987; see also Kosslyn et al., 1989) has reported that both a RVF/LH advantage for categorical processing and a LVF/RH advantage for coordinate processing are smaller for a group of ambidextrous subjects than for a group of strongly right-handed subjects. To test the generality of this result, we designed the present experiment to compare the Task × Visual Field interaction for right- and left-handers. The previous results reported by Kosslyn and his colleagues suggest that the specific Task × Visual Field interaction that has been obtained for right-handers will be reduced or eliminated for left-handers. Based in part on the differences that he and his colleagues obtained between right-handed and ambidextrous subjects, Kosslyn (1987) also suggested that individual subjects who show a relatively large LVF/RH advantage for coordinate tasks (such as Near–Far task) should show a relatively large RVF/LH advantage for categorical tasks (such as the Above–Below task). Although Hellige and Michimata (1989) failed to find support for this predicted correlation between the two tasks, their experiment was limited by the use of only right-handed subjects. Consequently, one purpose of the present experiment was to determine whether such a relationship would be present when left-handers are included.

Kosslyn (1987) also suggested originally that any left-hemisphere dominance for categorical spatial processing was related to left-hemisphere dominance for verbal processing. Although later hypotheses about the mechanisms that underlie hemispheric asymmetry for spatial processing do not emphasize this relationship (e.g., Kosslyn et al., 1992), whether it exists is, nevertheless, an interesting empirical question that can be addressed by looking at correlations between measures of asymmetry obtained from the spatial processing tasks used in the present experiment and measures of asymmetry obtained from the dichotic listening task used in Experiment 1 and the CVC identification task used in Experiment 4.

Method

Apparatus and stimulus materials. The apparatus and stimulus materials were identical to those used by Hellige and Michimata (1989). Subjects sat at a table facing a 44 × 48 cm screen approximately 60 cm away. A black posterboard covered the screen, except for two rectangular windows, one of which was located in each visual field, and for a small circular opening midway between the two windows. Each window measured 12 cm vertically × 4 cm horizontally, with the edge nearest the center of the screen being 1.7 cm from the center. During the experiment, each subject's chin was placed on a padded rest with a forehead-stabilization bar. Centered on the table in front of the subject was a response console measuring 17 × 35.5 cm. On top of the console were four buttons arranged in a row from left to right. The buttons were arranged in two pairs. The centermost button of each pair was located 7.5 cm from the center of the console and the two buttons within a pair were located 7.5 cm apart. For the Above–Below task, a small card with the same label (ABOVE or BELOW, counterbalanced across subjects) was placed above the two innermost buttons, and a small card with the opposite label was placed above the two outermost buttons. A similar arrangement was used for the Near–Far task, except that the two labels were NEAR and FAR. Visual stimuli and a fixation dot were rear-projected onto the screen at the appropriate times using a Gerbrands three-channel tachistoscope (Model G1176) equipped with two Kodak Carousel 850 slide projectors with Kodak Ektanar f/2.8 in. lenses. Stimulus duration was controlled by a Gerbrands six-channel timer (Model 300-6T) and summary statistics for each task were computed by an Apple IIe microprocessor.

The stimulus on each trial consisted of a horizontal line positioned halfway between the top and bottom edges of the viewing window and a small dot located in 1 of 12 positions above and below the line. When projected on the screen, the line and the dot appeared as white stimuli with a luminance of approximately 4.0 cd/m^2 on an opaque background. The dot subtended approximately 0.2° visual angle. Beginning with the position nearest the line, the possible positions of the dot were approximately 0.5, 1.0, 1.5, 2.5, 3.0, and 3.5° visual angle above or below the line. On different trials, the line-and-dot stimulus was projected to only the left window (LVF/RH trials), only the right window (RVF/LH trials), or to both windows simultaneously (redundant bilateral trials). The centermost edge of these lateralized stimuli was approximately 2.0° visual angle from the center of the screen. A fixation dot subtending approximately 0.2° visual angle with a luminance of approximately 4.0 cd/m^2 was projected at appropriate times to the center of the viewing screen.

During each of the two spatial processing tasks, each subject received a total of 144 experimental trials consisting of a random ordering of four 36-trial sets. Each 36-trial set consisted of each of the 12 dot positions presented one time in each of the three visual field conditions (LVF/RH, RVF/LH, bilateral). Within each 36-trial set, the trial types were arranged randomly with the restriction that no visual-field condition occur more than four times in a row.

Procedure. At the beginning of each task, subjects were told to place their index and middle fingers of the left and right hands on the innermost and outermost response keys, respectively, and to direct their gaze toward the fixation dot when it appeared. Subjects were told to maintain that eye fixation until after they had made their responses on each trial. While they were being instructed about the experimental task, subjects were given a sheet containing all 12 possible stimuli divided into the four categories defined by the orthogonal combination of whether the dot was above or below the line and whether the dot was near or far from the line.

For the Above–Below task, subjects were told to indicate as quickly and as accurately as possible whether the dot was above or below the line, ignoring the distance between the line and the dot. Subjects made their responses by simultaneously pressing either both index fingers or both middle fingers, with the assignment of fingers to above versus below responses counterbalanced across subjects. On each trial, reaction time (RT) was defined by the time of the first button press. Each trial began with the onset of the fixation dot for 1 s followed immediately by the line-and-dot stimulus for 150 ms. The intertrial interval was 5 s. Subjects received a set of 36 unscored practice trials before the experimental trials.

For the Near–Far task, subjects were taught to consider the three dot locations nearest the line on either side (within 2 cm of the line) to be *near* the line and to consider the three dot locations farthest from the line on either side to be *far* from the line. Subjects were told to indicate as quickly and as accurately as possible whether the dot was near the line or far from the line, ignoring whether it was above or below the line. Subjects made their responses by simultaneously pressing either both index fingers or both middle fingers, with the assignment of fingers to near versus far responses counterbalanced across subjects. Other aspects of the procedure were identical to those of the Above–Below task.

Results and Discussion

We computed for each subject the percentage of errors and the median RT of correct responses for each visual field condition during each of the two tasks. There was no evidence for different trade-offs between speed and accuracy for the two handedness groups, for the two tasks, or for the three visual-field conditions (LVF/RH, RVF/LH, bilateral). In fact, there was a high positive correlation ($r = .97$) between the mean percentage of errors and mean RT for the 12 conditions defined by the orthogonal combination of handedness, task, and visual field condition. The percentage of errors was too low for the Above–Below task (3.46%) to allow a meaningful statistical analysis of the error rate for that task. Accordingly, emphasis is placed on RT as the primary dependent variable. However, the higher percentage of errors for the Near–Far task (9.95%) does allow for a meaningful statistical analysis of error rate for that task, and significant effects will be noted for each handedness group after presentation of the RT results.

Right-handers. Performance data on the two spatial processing tasks were obtained from all 56 right-handed subjects. The RT values were subjected to an ANOVA with subjects' sex as a between-subjects variable and with task and visual field as within-subjects variables. There were no effects of subjects' sex, so we collapsed the results across this variable. The upper panel of Figure 1 shows the RTs for each of the three visual field conditions in each of the two tasks. As the upper panel of Figure 1 shows, responses were significantly faster for the Above–Below task than for the Near–Far task, $F(1, 54) = 42.85$, $MS_e = 32081.34$, $p < .001$. The main effect of visual field condition was also significant, $F(2, 108) = 18.10$, $MS_e = 960.94$, $p < .001$, with RTs being significantly faster to bilateral presentations ($M = 639$ ms) than to either LVF/RH ($M = 658$ ms) or RVF/LH ($M = 662$ ms) presentations and with the latter two conditions not differing from each other. Of particular theoretical importance was a significant Task × Visual Field interaction, $F(2, 108) = 3.77$, $MS_e = 717.57$, $p < .05$.

For the Above–Below task, there was a significant visual field effect, $F(2, 108) = 12.49$, $MS_e = 851.81$, $p < .001$, with RT being significantly faster for bilateral presentations ($M = 573$ ms) than for either LVF/RH ($M = 599$ ms) or RVF/LH ($M = 594$ ms) presentations. The trend toward a RVF/LH advantage for the Above–Below task did not approach statistical significance. In fact, for the Above–Below task, only 29 of the 56 right-handers (51.8%) showed faster RTs for RVF/LH trials than for LVF/RH trials (see Table 3). For the Near–Far task, there was again a significant visual field effect, $F(2, 108) = 11.45$, $MS_e = 826.71$, $p < .001$, with the pattern obtained on unilateral trials being different from that found for the Above–Below task. That is, RT was again significantly faster for bilateral presentations ($M = 705$ ms) than for either LVF/RH ($M = 717$ ms) or RVF/LH ($M = 731$ ms) presentations. However, for the Near–Far task, RT was significantly faster for LVF/RH than for RVF/LH presentations. This existence of a LVF/RH advantage for the Near–Far task is reinforced further by an analysis of the percentage of errors for that task: There were

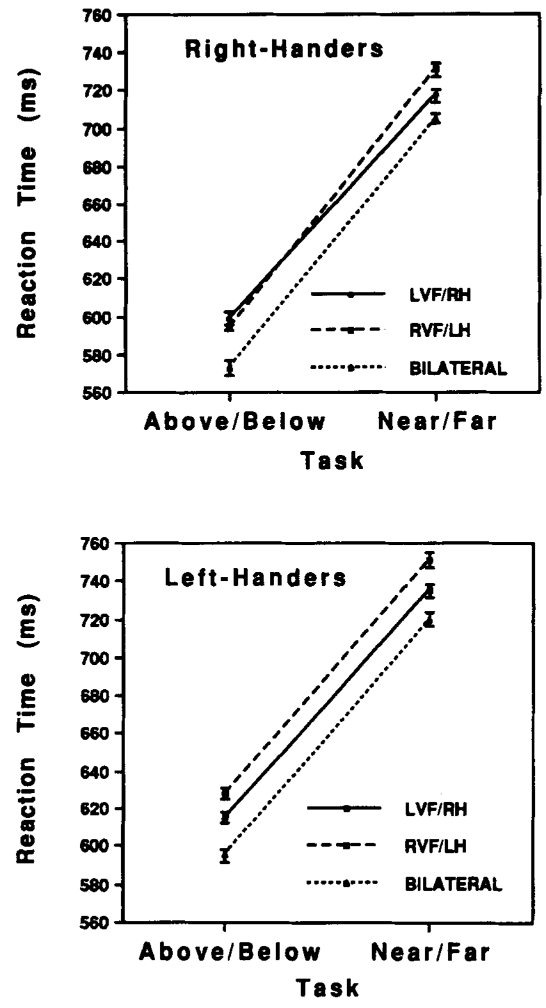

Figure 1. Reaction times of correct responses during the Above–Below and Near–Far spatial processing tasks. The parameter in each panel is visual field condition: left visual field/right hemisphere (LVF/RH), right visual field/left hemisphere (RVF/LH), and bilateral. Error bars for each task show the standard errors of the difference scores computed by subtracting each subject's mean score for that task from his or her score for each visual field condition within that task. The results for right- and left-handed groups are shown in the upper and lower panels, respectively.

Table 3
Number of Subjects With Right- or Left-Visual-Field Dominance for Processing Spatial Relationships

	Dominant visual field	
Handedness	Left (Right hemisphere)	Right (Left hemisphere)
	Above–Below task—reaction time	
Right	27	29
Left	37	21
	Near–Far task—reaction time[a]	
Right	41	14
Left	41	17
	Near–Far task—percentage of errors[b]	
Right	40	12
Left	34	14

[a] One right-hander showed no visual field difference. [b] Four right-handers and 10 left-handers showed no visual field difference.

significantly fewer errors for LVF/RH presentations (8.27%) than for RVF/LH presentations (10.83%), $F(1, 54) = 26.83$, $MS_e = 6.98$, $p < .001$.

Left-handers. Performance data on the two spatial processing tasks were obtained from 58 left-handed subjects (25 men and 33 women). The RT values were subjected to an ANOVA with subjects' sex and presence versus absence of familial sinistrality as between-subjects variables and with task and visual field as within-subjects variables. There were no effects of subjects' sex or of familial sinistrality, so we collapsed the results across these variables. The lower panel of Figure 1 shows the RTs for each of the three visual field conditions in each of the two tasks. As the lower panel of Figure 1 shows, responses were again significantly faster for the Above–Below task than for the Near–Far task, $F(1, 54) = 48.22$, $MS_e = 25{,}948.96$, $p < .001$. The main effect of visual field condition also was significant, $F(2, 108) = 31.30$, $MS_e = 723.45$, $p < .001$. Averaged across both tasks, RTs for left-handers were significantly faster to bilateral presentations ($M = 651$ ms) than to either LVF/RH ($M = 670$ ms) or RVF/LH ($M = 681$ ms) presentations, and RT was significantly faster to LVF/RH than to RVF/LH presentations. In contrast to the results obtained from right-handers, the Task × Visual Field interaction for left-handers did not even approach statistical significance ($F < 1$). Instead, for both the Above–Below and Near–Far tasks, RT was significantly faster for bilateral than for either type of unilateral presentation, and was significantly faster for LVF/RH than for RVF/LH presentation (see Figure 1, lower panel). The existence of a LVF/RH advantage for the Near–Far task is reinforced further by an analysis of the percentage of errors for that task: There were significantly fewer errors for LVF/RH presentations (9.36%) than for RVF/LH presentations (11.55%), $F(1, 55) = 14.78$, $MS_e = 9.68$, $p < .001$.

Note that for the Above–Below task the pattern of visual field effects on unilateral trials is not the same for left-handers and right-handers. Consequently, in an ANOVA for the Above–Below task that included handedness as a between-subjects variable, the Handedness × Visual Field interaction was marginally significant, $F(2, 222) = 2.58$, $MS_e = 807.14$, $.05 < p < .10$. For the Near–Far task, however, the pattern of visual field effects was virtually identical for left- and right-handers. Consequently, for that task the Handedness × Visual Field interaction did not even approach statistical significance, $F(2, 222) < 1$.

Table 3 shows the number of right- and left-handers who show RVF/LH versus LVF/RH advantages for (a) RT in the Above–Below task, (b) RT in the Near–Far task, and (c) percentage of errors in the Near–Far task. For the Above–Below task, a greater proportion of left-handers than of right-handers showed a LVF/RH advantage, with the difference approaching statistical significance, χ^2 $(1, N = 114) = 2.81$, $.05 < p < .10$. For the Near–Far task there were no significant differences related to handedness for either RT or percentage of errors.

The results obtained for right-handers are very similar to the results reported by Hellige and Michimata (1989), who used the same tasks. This is true with respect to the Task × Visual Field interaction, the significant LVF/RH advantage for RT and error rate during the Near–Far task, and the nonsignificant trend toward a RVF/LH advantage during the Above–Below task. The results for right-handers also replicate two findings reported by Hellige and Michimata concerning the relationship of performance on bilateral trials to performance on LVF/RH and RVF/LH trials. One finding is that performance on bilateral trials is better than on either of the two unilateral trials. For this sort of redundancy gain to occur, the two hemispheres must be able to cooperate, even if it is only to coordinate what may be largely independent decisions about the correct response. The second finding concerns the RT difference between the Above–Below and Near–Far tasks. As shown in the upper panel of Figure 1, the RT difference between the two tasks was significantly larger for RVF/LH trials ($M = 137$ ms) than for LVF/RH trials ($M = 118$ ms), $F(1, 55) = 5.07$, $MS_e = 449.64$, $p < .05$. As Hellige and Michimata noted, this type of Task × Visual Field interaction suggests that the two hemispheres process these line and dot stimuli in qualitatively different ways. They suggest that a left-hemisphere bias toward categorical spatial processing leads to relatively fast processing during the Above–Below task but to relatively slow processing during the Near–Far task. In contrast, a right-hemisphere bias toward coordinate spatial processing leads to slower processing during the Above–Below task (relative to the left hemisphere) but to faster processing during the Near–Far task (relative to the left hemisphere). As a result, the RT difference between the two tasks is smaller on LVF/RH trials than on RVF/LH trials. With this in mind, it is interesting that the RT difference between the tasks that was obtained on bilateral trials ($M = 134$ ms) is more similar to the difference obtained on RVF/LH trials than to the difference obtained on LVF/RH trials, with the difference between the patterns obtained on the latter two visual field conditions approaching statistical significance, $F(1, 55) = 2.88$, $MS_e = 921.82$, $.05 < p < .10$. Hellige and Michimata obtained the same pattern of results, which suggests that on bilateral trials subjects are biased toward the type of spatial processing that is favored on RVF/LH trials.

In some ways, the pattern of results obtained for left-handers is very similar to that obtained for right-handers, but in other ways the patterns are clearly different. Regardless of handedness, there was a significant LVF/RH over RVF/LH advantage for both RT and error rate during the Near–Far task. However, for left-handers, there was no Task × Visual Field interaction for RT. That is, the LVF/RH advantage extended to the Above–Below task. In fact, the LVF/RH advantage was the same magnitude for both tasks, so that the RT difference between the two tasks was identical on RVF/LH (M = 122 ms) and LVF/RH (M = 122 ms) trials. As a result of this, it is not possible to determine whether the RT difference obtained between tasks on bilateral trials (M = 125 ms) was more similar to one of the unilateral conditions than to the other. It is clear, however, that the redundancy gain on bilateral trials was approximately the same magnitude for left-handers as for right-handers. This suggests that handedness may be unrelated to the efficiency with which the hemispheres collaborate in the processing of identical stimuli.

The absence of a Task × Visual Field interaction for left-handers in the present experiment is similar in some ways to results that have been reported for ambidextrous subjects who have completed categorical and coordinate spatial processing tasks (e.g., Kosslyn, 1987; Kosslyn et al., 1989). However, the specific pattern obtained in the present experiment also differs in important ways from that reported by Kosslyn and his colleagues. In their study, there was no Task × Visual Field interaction for ambidextrous subjects, because there was no significant visual field difference for either their categorical or their coordinate task. In the present experiment, however, there is no Task × Visual Field interaction for left-handers, because there is a significant LVF/RH advantage for both tasks. The reasons for these discrepancies are not clear and are unlikely to be resolved without additional studies. One possibility is that certain aspects of hemispheric asymmetry differ for ambidextrous subjects (who have little in the way of a systematic hand preference) and the left-handed subjects used in the present experiments. The present results, taken at face value and combined with those of Kosslyn and his colleagues, suggest that for left-handers the right hemisphere is superior to the left for both categorical and coordinate aspects of spatial processing, whereas for ambidextrous subjects both hemispheres have equal abilities for categorical and coordinate aspects of spatial processing. This sort of interpretation must be considered with caution, however, because the specific tasks used by Kosslyn and his colleagues were different from the tasks we used in the present experiment.

As noted in the introduction to the present experiment, the fact that the same subjects participated in both the Above–Below and Near–Far tasks (and in the other experiments reported in this article) makes it possible to examine various predictions having to do with possible relationships among measures of hemispheric asymmetry obtained from the various tasks. For convenience of exposition, presentation of the pattern of relationships is postponed until after Experiment 4 has been described and discussed.

Experiment 4: CVC Syllable Identification

Experiment 4 required subjects to identify CVC nonsense syllables presented briefly to the LVF/RH, RVF/LH, or to both visual fields (and hemispheres) simultaneously (redundant bilateral presentation). Previous experiments have consistently yielded a RVF/LH over LVF/RH advantage for identifying CVC stimuli, with the advantage attributed to superiority of the left hemisphere for linguistic or phonetic processing (e.g., Hellige, Cowin, & Eng, in press; Hellige, Cowin, Eng, & Sergent, 1991; Hellige, Taylor, & Eng, 1989; Levy et al., 1983a). Furthermore, the pattern of errors has been qualitatively different on RVF/LH and LVF/RH trials, suggesting that the two hemispheres process the CVC stimuli in different ways. In addition, performance on redundant bilateral trials has been used to shed light on issues related to interhemispheric interaction. This task was chosen for the present study for the following reasons.

The CVC identification task measures several different aspects of hemispheric asymmetry. The difference in overall error rate between LVF/RH and RVF/LH trials provides an indication of the direction and magnitude of hemispheric superiority for CVC identification. The difference between the overall error rate on redundant bilateral trials and the better of the two unilateral trials is a measure of the efficiency with which the two hemispheres can coordinate their activities. That is, a larger redundancy gain (fewer errors on bilateral trials than on the better of the two unilateral trials) suggests more efficient interhemispheric coordination than does a smaller redundancy gain (see Mohr, Pulvermüller, & Zaidel, 1994). As we discuss in more detail below, differences in the qualitative error patterns obtained on RVF/LH and LVF/RH trials provide an indication of the extent to which the two hemispheres are biased toward processing the CVC stimuli in different ways or by applying different strategies. Furthermore, examining whether the qualitative error pattern on redundant bilateral trials is more like the pattern obtained on RVF/LH trials or more like the pattern obtained on LVF/RH trials provides a measure of which hemisphere's strategy is preferred when viewing conditions do not create a bias in favor of one hemisphere or the other. Thus, the CVC identification task allows effects related to handedness and subjects' sex to be examined for a number of different aspects of hemispheric asymmetry and interhemispheric interaction.

Previous visual half-field studies that have used the identification of words or nonsense syllables have not found systematic differences between men and women (e.g., Hellige et al., 1989, 1991, in press; Levy et al., 1983a; see also Hiscock et al., 1991). The RVF/LH over LVF/RH advantage with overall error rate as the dependent variable has been found for left-handers as well as right-handers, although the magnitude of the RVF/LH advantage is often smaller for the left-handed group (for reviews and examples, see Bradshaw, 1989; Bryden, 1982; Dagenbach, 1986;

Hellige, 1993a; Krutsch & McKeever, 1990). The studies that have compared right- and left-handers have not, however, included analysis of the qualitative error patterns associated with each visual field and have not included redundant bilateral trials. Consequently, one purpose of the present experiment was to expand on these previous studies in the ways that have been indicated.

The details of the present experiment and analysis were patterned after the studies of CVC identification reported by Hellige et al. (1989). To examine the qualitative nature of CVC processing, errors were classified into three theoretically motivated types that Levy et al. (1983a) had suggested earlier. A first-letter error (FE) occurred when the first letter of the CVC was missed but the last letter was correct (e.g., CAG or CEG as responses to DAG), and a last-letter error (LE) occurred when the last letter of the CVC was missed but the first letter was correct (DAC or DEC as responses to DAG). All other types of errors were categorized as other errors (OEs). For each visual field condition these error data were normalized by dividing the number of each type of error by the total number of errors for that visual field condition. Such normalized scores provide an indication of the qualitative error pattern corrected for differences in overall error rate among the visual field conditions.

Using these normalized FE, LE, and OE scores, Hellige et al. (1989) found significantly different error patterns on LVF/RH and RVF/LH trials. Specifically, on LVF/RH trials, participants failed to identify the last letter far more often than the first letter; that is, there were many more normalized LEs than FEs. On RVF/LH trials, the difference between the number of normalized LEs and FEs was significantly smaller. Similar results have been reported by Levy et al. (1983a), by Hellige et al. (1991, in press), and by Eng and Hellige (1994). Levy et al. and Hellige and colleagues have suggested that the large difference between the number of FEs and LEs on LVF/RH trials occurs because the right hemisphere lacks phonetic processing ability and consequently treats the CVC stimulus as three individual letters and processes them in a relatively slow, sequential manner. The more equal number of FEs and LEs on RVF/LH trials is consistent with suggestions that the left hemisphere distributes attention more evenly or more rapidly across the letter positions in a multi-letter display, perhaps because of its superior phonetic processing ability (for additional discussion, see Eng & Hellige, 1994, and Hellige et al., in press).

In addition to providing information about differences between processing on LVF/RH and RVF/LH trials, the CVC identification paradigm we used in the present experiment also permits examination of quantitative and qualitative aspects of processing when viewing conditions do not bias processing in favor of one hemisphere or the other (e.g., on redundant bilateral trials). As might be expected with presentation of two copies of the same CVC stimulus, the overall error rate on redundant bilateral trials has been as low as or even lower than the overall error rate on RVF/LH trials. Because the two redundant stimuli are presented directly to different hemispheres, the low error rate on bilateral trials indicates efficient communication between the hemispheres. Despite the low error rate, the pattern of normalized FEs, LEs, and OEs on bilateral trials has not been identical to the pattern obtained on RVF/LH trials—which is the pattern associated with superior performance on unilateral trials. Instead, the bilateral error pattern has been more similar to the pattern obtained on LVF/RH trials for most subjects (e.g., Hellige, 1993a, 1993b; Hellige et al., 1989, in press). The similarity of the qualitative error pattern on bilateral and LVF/RH trials suggests that when both hemispheres receive exactly the same information, the mode of letter processing favored by the right hemisphere often dominates, perhaps because a letter-by-letter mode of processing can be used efficiently by both hemispheres, whereas a more phonetic mode of processing would be restricted to the left hemisphere. Including redundant bilateral trials in the present experiment provides the opportunity to determine whether such effects are related to handedness.

It is also important to determine whether the measures of asymmetry obtained from the present experiment are related to the measures of asymmetry obtained from Experiments 1–3. Because CVC identification clearly involves phonetic processing and produces a RVF/LH advantage, there are a priori reasons to suppose that the asymmetries observed in the present experiment are correlated with the ear difference obtained in the linguistic dichotic listening task used in Experiment 1. For example, individuals who show a relatively large right-ear advantage in the dichotic listening task might be expected to show a relatively large RVF/LH advantage in the present experiment (e.g., Dagenbach, 1986; Hines & Satz, 1974; Krutsch & McKeever, 1990). In addition, Hellige and Wong (1983) found that the larger the right-ear advantage, the greater the tendency for an individual to rely selectively on processing resources of the left hemisphere during a reading task. This suggests the possibility of a relationship between ear advantage in Experiment 1 and the extent to which the qualitative error pattern obtained on redundant bilateral trials is more similar to the error pattern obtained on LVF/RH trials than to the error pattern obtained on RVF/LH trials. Finally, to the extent that any left-hemisphere superiority for processing categorical spatial relationships depends on left-hemisphere superiority for verbal processing (see Experiment 3), the asymmetries observed in the present experiment should be correlated with visual field differences for the Above–Below task used in Experiment 3.

Method

Apparatus and stimulus materials. The apparatus, stimulus materials, and procedures were identical to those used by Hellige et al. (1989). Stimuli were 37 CVC nonsense syllables, with the three letters arranged vertically. The CVCs were constructed by using the uppercase consonants D, F, G, K, P, S, and T; and the uppercase vowels A, E, and O. The stimuli were prepared by using uppercase Futura Medium press-on letters, which were photographed for presentation in one channel of a Scientific Prototype Model N–1000A three-field tachistoscope. When projected in the tachistoscope, the CVCs appeared as white letters on an opaque background. On LVF/RH and RVF/LH trials, the edge of the CVC nearest the center was displaced approximately 1.5° visual angle from the center. On redundant bilateral trials, the same CVC stimulus was presented simultaneously to both LVF and RVF locations. Each CVC spanned approximately 0.5° visual angle horizontally and 1.5° visual angle vertically. An additional set of 12 CVC stimuli were prepared in the same manner and were used during a practice block that preceded the actual experimental trials.

A pattern mask was prepared by arranging letter segments in a rectangle. Two copies of the mask were arranged and photographed so that each copy would overlap completely each of the two visual field positions. When projected in the tachistoscope, each of the two identical masking stimuli spanned approximately 1.5° visual angle horizontally and 2.0° visual angle vertically. The masking stimuli were centered so that the centermost edge of each was located approximately 1.0° visual angle from the center of the viewing field. A circular red light-emitting diode, spanning approximately 0.5° visual angle, appeared in the center of the viewing field and served as a fixation stimulus.

Experimental trials were arranged in three 37-trial sets, the first item in each set was not scored. The order of these three sets was determined randomly for each subject. Across the entire sequence of 108 scored experimental trials, each of the 36 CVC stimuli appeared one time in each of the three visual field conditions (LVF/RH, RVF/LH, bilateral). However, each of the 36 CVCs appeared only once in each of the three stimulus sets. Within each set, the 36 scored stimuli were arranged randomly with the restrictions that (a) each of the three visual field conditions was represented 12 times, (b) each visual field condition was preceded equally often by each of the three conditions, and (c) the same visual field condition was not presented more than four times in a row. Similar procedures were used to construct a sequence of 36 practice trials. The first (unscored) trial in each experimental set provided the appropriate preceding visual field condition for the first scored trial in that set.

Procedure. Subjects initiated each trial by pressing a foot pedal. When the pedal was pressed, the fixation dot was presented for 2 s. The dot was followed immediately by a CVC stimulus for a duration determined on each trial using the titration procedure outlined below. The CVC stimulus was followed immediately by the masking stimulus presented to both visual fields for a duration of 200 ms. Subjects were instructed to fixate their gaze on the red dot when it appeared and to maintain that fixation throughout the trial. Subjects identified the syllable by first pronouncing it and then spelling it.

To keep the overall error rate at approximately 50% for each subject, exposure duration for the CVC stimulus was constantly varied throughout the experiment. Subjects began the 36-trial practice sequence with a CVC duration of 200 ms. After each correct response, the exposure duration was adjusted downward by 10 ms until a duration of 150 ms was reached, after which adjustment was by 5 ms. After each incorrect response the exposure duration was adjusted upward by 5 or 10 ms (depending on whether the last duration used was above or below 150 ms). However, the exposure duration was never increased beyond 200 ms. This adjustment procedure was continued throughout the experiment.

Results

Right-handers. Performance on the CVC identification task was obtained from 54 right-handers, 25 men and 29 women. Averaged across all right-handers and all three visual field conditions, the method used to adjust stimulus duration from trial to trial was successful in producing an overall CVC identification error rate of approximately 50% (specifically, 48.1%). The method was also successful in producing stimulus durations that were approximately equal for the three visual field conditions (LVF/RH $M = 65$ ms, RVF/LH $M = 65$ ms, bilateral $M = 64$ ms). Thus, differences among the visual field conditions in overall error rates and in the qualitative error pattern cannot be attributed to inadvertent differences among the fields in mean stimulus duration.

We conducted an ANOVA on the number of errors made by right-handers that included subjects' sex as a between-subjects variable and visual field condition as a within-subjects variable. The only significant effect obtained in this analysis was the main effect of visual field condition, $F(2, 104) = 56.60$, $MS_e = 15.00$, $p < .001$. As the data in Figure 2 suggest, the percentage of errors was significantly greater on LVF/RH trials than on either RVF/LH or bilateral trials ($ps < .001$) and also tended to be greater on RVF/LH trials than on bilateral trials ($.05 < p < .10$).

To examine qualitative differences in processing the CVC stimuli, qualitative error (QE) scores were computed for each visual field condition using the method outlined by Levy et al. (1983a). Specifically, for each visual field, QE = (LE − FE)/TE, where LE is the number of last-letter errors, FE is the number of first-letter errors, and TE is the total number of errors for that visual field. Recall that a LE occurs if the last letter is missed but the first letter is correct, and a FE occurs if the first letter is missed but the last letter is correct (correctness of the vowel is irrelevant). Note that larger QE scores occur to the extent that the number of LEs is greater than the number of FEs. We subjected QE scores for right-handers to an ANOVA with subjects' sex as a between-subjects variable and with visual field condition as

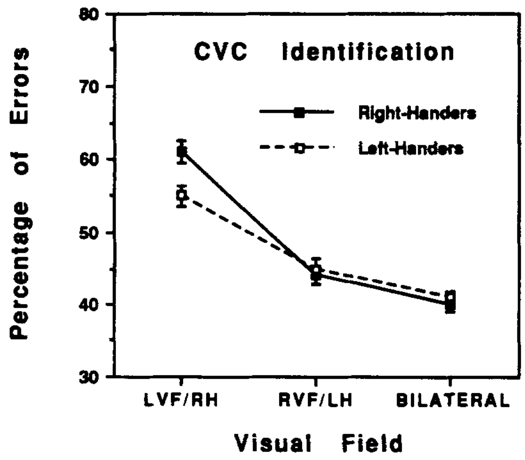

Figure 2. Percentage of consonant–vowel–consonant (CVC) identification errors for right-handed and left-handed groups in each of the three visual field conditions: left visual field/right hemisphere (LVF/RH), right visual field/left hemisphere (RVF/LH), and bilateral. Error bars show the standard errors of the difference scores computed by subtracting each subject's mean score from his or her score for each visual field condition.

a within-subjects variable. Figure 3 shows the QE scores for the three visual field conditions for men and women. The results for right- and left-handers are shown in the upper and lower panels, respectively.[1]

As suggested by the upper panel of Figure 3, the QE scores were significantly larger for women than for men, producing a main effect of subjects' sex, $F(1, 52) = 6.80$, $MS_e = 0.118, p < .025$. Of particular theoretical importance was a significant main effect of visual field, $F(2, 104) = 19.11$, $MS_e = 0.032$, $p < .001$. The interaction of visual field with subjects' sex did not approach statistical significance ($F < 1$).

Consistent with the results of earlier experiments, the QE scores were significantly greater on LVF/RH than on RVF/LH trials, $F(1, 52) = 29.41$, $MS_e = 0.041, p < .001$.

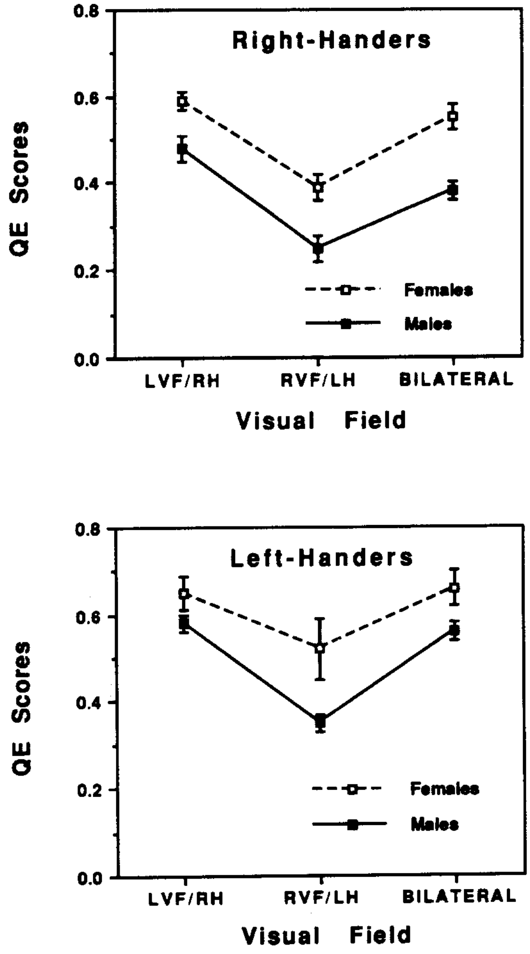

Figure 3. Qualitative error (QE) scores obtained during the consonant–vowel–consonant identification task for each of the three visual field conditions: left visual field/right hemisphere (LVF/RH), right visual field/left hemisphere (RVF/LH), and bilateral. The parameter in each panel is sex of the subject. Error bars show the standard errors of the difference scores computed by subtracting each subject's mean score from his or her score for each visual field condition. The results for right- and left-handed groups are shown in the upper and lower panels, respectively.

The QE scores obtained on redundant bilateral trials were intermediate between the QE scores obtained on RVF/LH and LVF/RH trials and were significantly different from both: For RVF/LH versus bilateral trials, $F(1, 52) = 15.27$, $MS_e = 0.035, p < .001$; for LVF/RH versus bilateral trials, $F(1, 52) = 6.00$, $MS_e = 0.022$, $p < .025$. However, consistent with the results of earlier experiments, the QE scores obtained on bilateral trials were more similar to the QE scores obtained on LVF/RH trials than to the QE scores obtained on RVF/LH trials. To examine this, we computed a CVC bias score for each subject, as an indication of the extent to which the pattern of errors obtained on bilateral trials was more similar to the qualitative pattern obtained on LVF/RH versus RVF/LH trials. Specifically, CVC bias = $|\mathrm{LVF_{QE}} - \mathrm{BVF_{QE}}| - |\mathrm{RVF_{QE}} - \mathrm{BVF_{QE}}|$, where $\mathrm{LVF_{QE}}$ is the QE score obtained on LVF/RH trials, $\mathrm{RVF_{QE}}$ is the QE score obtained on RVF/LH trials, and $\mathrm{BVF_{QE}}$ is the QE score obtained on bilateral trials. Note that by taking the absolute value of the $(\mathrm{LVF_{QE}} - \mathrm{BVF_{QE}})$ difference score, the first part of this equation provides a measure of the difference between qualitative error patterns on LVF/RH and bilateral trials, regardless of the direction of any difference between the two scores. Likewise, the second part of the equation provides a measure of the difference between qualitative error patterns on RVF/LH and bilateral trials, again regardless of the direction of any difference between the two scores. As a result, the CVC bias index takes on positive values when the bilateral error pattern is more similar to the RVF/LH pattern than to the LVF/RH pattern and takes on negative values when the bilateral error pattern is more similar to the LVF/RH pattern than to the RVF/LH pattern. For right-handers, the mean CVC bias score of -0.08 was significantly less than 0, $t(53) = -2.67$, $p < .025$.

Left-handers. Performance data on the CVC identification task were obtained from 61 left-handers, 28 men and 33 women. Averaged across all left-handers and all three visual field conditions, the overall CVC identification error rate was approximately 50% (specifically, 46.8%). As was the case for right-handers, the method of adjusting stimulus duration was successful in producing stimulus durations that were equal for the three visual field conditions (LVF/RH

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[1] The error patterns from the present experiment have also been analyzed by computing normalized FE, LE, and OE scores (as described in earlier portions of the text) and examining those scores in ANOVAs with subjects' sex as a between-subjects variable and with visual field condition and error type as within-subjects variables. The results of these analyses lead to the same conclusions as the analyses using QE scores. For example, the significant main effect of visual field that emerges in the analysis of QE scores emerges as a significant Error Type (FE, LE, OE) × Visual Field interaction in the alternative analyses. In addition, both ways of analyzing the error patterns have also produced equivalent results in earlier studies (e.g., Hellige et al., 1989, 1991, in press). We report the QE analyses in the present experiment because the computation of such scores has been motivated by theory (see Levy et al., 1983a), because such analyses allow for briefer presentation of the important results, and because the QE scores are amenable to the examination of individual differences.

M = 82 ms, RVF/LH M = 82 ms, bilateral M = 82 ms). However, the mean duration (82 ms) required for left-handers to be correct approximately 50% of the time was significantly longer than the duration (65 ms) required for right-handers, $t(110) = 2.60, p < .025$.

We conducted an ANOVA on the number of errors made by left-handers that included subjects' sex and presence versus absence of familial sinistrality as between-subjects variables and visual field condition as a within-subjects variable. The only significant effect in this analysis was the main effect of visual field condition, $F(2, 114) = 25.81$, $MS_e = 16.13, p < .001$. As the data in Figure 2 suggest, the percentage of errors was significantly greater on LVF/RH trials than on either RVF/LH or bilateral trials ($ps < .001$) and was significantly greater on RVF/LH trials than on bilateral trials ($p < .05$). Although the pattern of visual field differences was very similar for right- and left-handers, an ANOVA that included handedness as a between-subjects variable revealed a significant Handedness × Visual Field interaction, $F(2, 222) = 3.38$, $MS_e = 15.63, p < .05$. As illustrated in Figure 2, the percentage of errors on LVF/RH trials was significantly lower for left-handers than for right-handers, whereas on RVF/LH and bilateral trials the percentage of errors was nonsignificantly higher for left-handers than for right-handers. As a result of this pattern, the RVF/LH over LVF/RH advantage was smaller for left- than for right-handers.

The upper portion of Table 4 shows the number of right- and left-handers who identified more CVC stimuli from the left versus the right visual fields. Although the proportion of left-handers who show a RVF/LH advantage is somewhat smaller than the proportion of right-handers who show such an advantage, this difference between right- and left-handers was not statistically significant, $\chi^2\ (1, N = 101) = 1.23$.

Table 4
Number of Subjects With Right- or Left-Visual-Field Dominance for CVC Identification

	Handedness	
Asymmetry	Right	Left
	Overall percentage of errors[a]	
Dominant visual field		
Right	42	42
Left	6	11
	QE scores[b]	
Visual field with larger QE score		
Right	14	18
Left	39	39
	CVC bias scores[c]	
Dominant error pattern on bilateral trials		
Negative (LVF/RH)	35	29
Positive (RVF/LH)	16	28

Note. CVC = consonant–vowel–consonant; QE = qualitative error; LVF/RH = left visual field/right hemisphere; RVF/LH = right visual field/left hemisphere. See text for explanation of QE and CVC bias score computation.
[a] Six right-handers and 8 left-handers identified an equal number of stimuli from both visual fields. [b] One right-hander and 4 left-handers showed no visual field difference. [c] Three right-handers and 4 left-handers had a CVC bias score of 0.

Both the existence of a significant RVF/LH advantage for left-handers and the fact that the advantage is smaller for left-handers than for right-handers are consistent with the results of previous experiments that have required subjects to identify words and nonsense syllables presented tachistoscopically (e.g., Bradshaw, 1989; Bryden, 1982; Hellige, 1993a; Krutsch & McKeever, 1990). In the present experiment, the reduced RVF/LH advantage for left-handers is caused primarily by the fact that left-handers make significantly fewer errors than do right-handers on LVF/RH trials (see Figure 2). This specific pattern of results is consistent with the hypothesis that left-handers are more likely than right-handers to process linguistic stimuli efficiently when they are presented to the right cerebral hemisphere (e.g., Bradshaw, 1989; Bryden, 1982, Hellige, 1993a). Figure 2 also shows that the redundancy gain on bilateral trials is equivalent for right- and left-handers. This is consistent with the results obtained on bilateral trials in Experiment 3 and again suggests that handedness may be unrelated to the ability of the hemispheres to collaborate in the processing of identical stimuli.

We subjected the QE scores for left-handers to an ANOVA with subjects' sex and presence versus absence of familial sinistrality as between-subjects variables and with visual field condition as a within-subjects variable. None of the effects involving familial sinistrality approached statistical significance, so we collapsed the results across that variable. The lower panel of Figure 3 shows the QE scores for the three visual field conditions for male and female left-handers.

As was the case for right-handers, the QE scores were significantly larger for women than for men, $F(1, 57) = 6.41$, $MS_e = 0.122$, $p < .025$. As was also the case for right-handers, there was a highly significant main effect of visual field, $F(2, 114) = 10.77, MS_e = 0.061, p < .001$. For left-handers, the QE scores were significantly greater on LVF/RH trials than on RVF/LH trials, $F(1, 57) = 12.76$, $MS_e = 0.082$, $p < .001$. The QE scores obtained on redundant bilateral trials were significantly larger than the QE scores obtained on RVF/LH trials, $F(1, 57) = 12.62, MS_e = 0.074$, $p < .001$, but not significantly different from the QE scores obtained on LVF/RH trials ($F < 1$). The CVC bias score was again computed for each subject as an indication of the extent to which the pattern of errors obtained on bilateral trials was more similar to the qualitative pattern obtained on LVF/RH versus RVF/LH trials. The mean CVC bias score was -0.078, with the difference from 0 approaching statistical significance, $t(60) = -1.73$, $.05 < p < .10$.

With respect to the QE scores, the pattern of results is similar for left-handers and right-handers. Consequently, in an ANOVA that included handedness as a between-subjects variable, neither the Handedness × Visual Field interaction nor the Handedness × Sex of Subject interaction approached statistical significance. There was, however, a significant main effect of handedness, $F(1, 111) = 9.74$, $MS_e = 0.118$, $p < .01$. As one can see by comparing the upper and lower panels of Figure 3, the QE scores were larger for left-handers than for right-handers. The only other significant effects in this ANOVA confirmed the main effects of visual field, $F(2, 222) = 26.05$, $MS_e = 0.047$, and sex of subject, $F(1, 111) = 13.70$, $MS_e = 0.011$, $p < .001$.

The middle portion of Table 4 shows the number of right- and left-handers whose QE scores were larger in the left versus right visual fields. The proportion of left-handers who show larger QE scores in the LVF/RH is slightly smaller than the proportion of right-handers who show such an effect, but this difference between right- and left-handers was not statistically significant, χ^2 $(1, N = 110) = 0.36$.

Despite the fact that the overall RVF/LH advantage was smaller for left-handers than for right-handers (Figure 2), the visual field difference in qualitative error pattern was virtually identical for the two groups (Figure 3). This provides an interesting dissociation between the quantitative and the qualitative measures of performance asymmetry. As noted earlier, the quantitative measure (total error rate) suggests that left-handers, relative to right-handers, are able to process the CVC stimuli efficiently when they are presented to the right cerebral hemisphere. At the same time, the qualitative measure (QE scores) suggests that the processing biases or strategies of the two hemispheres differ in the same way for left-handers that they do for right-handers. Thus, left-handers do not achieve better CVC identification than do right-handers on LVF/RH trials because they are more likely on those trials to apply the so-called "left-hemisphere" processing strategy that is associated with lower QE scores and with better performance. In fact, the QE scores were uniformly *larger* for left-handers than for right-handers. This suggests that, if anything, left-handers rely more than do right-handers on the relatively slow letter-by-letter processing that seems to be characteristic of the right hemisphere and do so, to some extent, regardless of which visual field is stimulated. To the extent that this slow letter-by-letter strategy is less efficient than the strategy that produces smaller QE scores, the CVC identification task should be more difficult for left-handers than for right-handers. The overall proportion of errors was nearly identical for right- and left-handers, but this is misleading because it is an artifact of the procedure used to adjust stimulus duration from trial to trial. However, the stimulus duration required to reach 50% accuracy was significantly longer for left- than for right-handers, indicating that the task was indeed more difficult for left-handers.

With respect to the QE pattern on redundant bilateral trials, the relationship to handedness is not completely clear. As noted earlier, with QE scores as the dependent variable, there was no interaction of handedness and visual field. In addition, the mean CVC bias score (which compares the error pattern on bilateral trials with the patterns obtained on each type of unilateral trial) are virtually identical for the two groups. These results suggest that both right- and left-handers tend to produce a pattern of errors on bilateral trials that is more similar to the pattern obtained on LVF/RH trials than to the pattern obtained on RVF/LH trials. However, the distribution of CVC bias scores suggests an interesting difference between right- and left-handers. As the lower portion of Table 4 shows, 35 of 54 right-handers produced a negative CVC bias score, but only 29 of 61 left-handers did so (recall that negative values indicate that the bilateral error pattern is more similar to the LVF/RH error pattern than to the RVF/LH error pattern), with this difference in the distribution of subjects approaching statistical significance, χ^2 $(1, N = 108) = 3.54$, $.05 < p < .10$. In addition, the variance of the CVC bias scores is significantly larger for left-handers (.126) than for right-handers (.047), $F(53, 60) = 2.68$, $p < .001$. Thus, left-handers seem more variable than right-handers in terms of which hemisphere's strategy they prefer when viewing conditions do not create a bias in favor of one hemisphere or the other.

The general absence of effects related to subjects' sex is consistent with the results of previous CVC identification experiments (e.g., Eng & Hellige, 1994; Hellige et al., 1989, 1991, in press; Levy et al., 1983a). In fact, in the present experiment the only effect related to sex was the finding that, for both right- and left-handers, the QE scores for women were significantly larger than the QE scores for men (Figure 3). In view of the facts that (a) no effects of this sort have been reported in previous CVC identification experiments; and (b) the effects do not interact with visual field, they will not be considered further.

Interrelations Among the Tasks

The results of Experiments 1–4 indicate that groups composed of right- and left-handed individuals differ with respect to several aspects of hemispheric asymmetry and interhemispheric interaction. The various performance asymmetries tend to be larger, on average, for right-handed groups than for left-handed groups, regardless of direction of the asymmetries. The consistency of such group differences could be taken to suggest that these various performance asymmetries are related to each other such that relatively large asymmetry for one task is associated with relatively large asymmetry for the other tasks. This sort of extension of *group* results is often implied by statements to the effect that a typical left-handed *individual* tends to show less asymmetry than a typical right-handed individual across a wide range of tasks. However, the group differences that we have found do not necessarily imply that this is the case. That is, the group differences do not indicate whether or not the individuals who show a relatively large performance asymmetry for one task are the same individuals who also show a relatively large performance asymmetry for other tasks. With this in mind, the purpose of the analyses in the present section is to determine which performance asymmetries are related to each other in this way and which are not and to learn more about the nature of those relationships that do exist.

One way of investigating the extent to which the aspects of hemispheric asymmetry measured by each task are related to the aspects of hemispheric asymmetry measured by other tasks is to compute for each task one or more laterality scores that reflect the direction and magnitude of relevant performance asymmetries and to examine the pattern of correlations among these laterality scores. Accordingly, we computed the following measures and examined the correlations among them. Left-side versus right-side difference scores were obtained for the auditory dichotic listening task (Index 1 in Table 5), the free-vision face task (Index 2 in Table 5), the Above–Below spatial processing task using RT as the dependent variable (Index 3 in Table 5), the Near–Far spatial processing task using RT as the dependent variable (Index 4 in Table 5), the Near–Far spatial processing task using percentage of errors as the dependent variable (Index 5 in Table 5), and the CVC identification task using the overall percentage of errors as the dependent variable (Index 6 in Table 5). We computed the difference scores for each of these measures so that positive values indicate left-hemisphere dominance and negative values indicate right-hemisphere dominance. To measure hemispheric asymmetry in qualitative error patterns, we subtracted the QE score obtained on RVF/LH trials from the QE score

Table 5

Correlation of Laterality Measures Across Tasks for All Subjects, Right-Handers, and Left-Handers

Index	1	2	3	4	5	6	7	8
1. Auditory								
All	—							
RH	—							
LH	—							
2. Faces								
All	−.07	—						
RH	−.18	—						
LH	−.04	—						
3. A–B RT								
All	.13	.01	—					
RH	.10	−.04	—					
LH	.11	−.03	—					
4. N–F RT								
All	.07	−.07	−.01	—				
RH	.02	−.04	.19	—				
LH	.10	−.09	−.15	—				
5. N–F errors								
All	.05	−.08	−.03	−.01	—			
RH	.16	−.13	−.01	−.12	—			
LH	−.01	−.04	−.04	.08	—			
6. CVC								
All	.31**	−.10	.17	.03	.01	—		
RH	−.02	−.01	.06	−.01	.15	—		
LH	.51**	−.23	.19	.06	−.07	—		
7. CVC QE								
All	−.07	.06	.01	.02	−.03	−.01	—	
RH	−.16	−.03	.00	−.20	−.06	−.01	—	
LH	−.04	.09	−.01	.15	−.01	−.04	—	
8. CVC bias								
All	.24**	−.12	.15	−.21	.04	−.01	−.61*	—
RH	.38**	−.22	−.02	−.09	.06	−.09	−.35*	—
LH	.19	.01	.23	−.29	.03	.03	−.73*	—

Note. For Indexes 1, 2, 3, 4, 5, and 6, left-side versus right-side difference scores were computed so that positive values indicate left-hemisphere dominance and negative values indicate right-hemisphere dominance. For Index 7, a positive value indicates that the qualitative error (QE) score was higher on left visual field/right hemisphere (LVF/RH) trials. For Index 8, a positive value indicates that the bilateral error pattern is more similar to the right visual field/left hemisphere (RVF/LH) pattern than to the LVF/RH pattern. A–B = Above–Below task; RT = reaction time; N–F = Near–Far task; CVC = consonant–vowel–consonant; All = all subjects; RH = right-handers; LH = left-handers.

* correlations not of a priori interest but with $p < .01$. ** correlations of a priori interest and $p < .05$.

obtained on LVF/RH trials (Index 7 in Table 5). Positive values of the resulting CVC QE index indicate that the QE score was larger on LVF/RH trials than on RVF/LH trials, which is the direction of the group difference in qualitative error patterns (see Figure 3). The final CVC bias measure (Index 8 in Table 5) indicates the extent to which the qualitative pattern of errors obtained on bilateral trials during CVC identification was more similar to the qualitative pattern obtained on LVF/RH trials versus RVF/LH trials. As noted earlier, the CVC bias index takes on positive values when the bilateral error pattern is more similar to the RVF/LH pattern than to the LVF/RH pattern, and it takes on negative values when the bilateral error pattern is more similar to the LVF/RH pattern than to the RVF/LH pattern.

Table 5 shows the correlations of these laterality measures across tasks for all subjects combined ($N = 112$), for right-handers ($n = 54$), and for left-handers ($n = 58$). We computed each correlation coefficient using the total number of subjects of the appropriate handedness type who provided all 8 relevant scores.

Homogeneity of correlation matrices for right- and left-handed subjects was tested using LISREL 8.1 (Jöreskog & Sörbom, 1993), a computer program designed to examine covariance structures in one or more groups. A two-group procedure was used, in which equality constraints across groups of handedness were made separately for the 8 × 8 matrix of correlations and for the 8 variances. This distinction was deemed necessary to separate group effects in variability (which might be attributable to such things as group differences in the range of asymmetries) from group effects in correlations. A model with the correlations constrained to be equal across handedness, but with variances free to vary, did not fit the data well [$\chi^2 = 44.11$ (28, $N = 112$), $p < .05$], suggesting some group differences in correlations. An inspection of the observed correlations within each group, however, shows rather small differences, by and large (see Table 5). In fact, in only 2 of 28 cases were the correlations significantly different for right- versus left-handers ($p < .05$). We discuss these two cases later. With respect to the pooled correlations computed for all 112 subjects, a model with the correlations constrained to be equal to 0 did not fit the data well [$\chi^2 = 97.95$ (28, $N = 112$), $p < .001$], indicating that some of the correlations are different from 0. To follow up the results of this omnibus test, individual correlations were examined using a .05 level of significance for those correlations in which there was interest a priori (as noted in the presentation of individual experiments) and using the .01 level of significance for all other correlations.

Perhaps the most striking thing about the data shown in Table 5 is the fact that very few of the correlation coefficients were significantly different from 0, and those that were tended to be small. The independence of most of these different laterality measures is consistent with the findings of several other studies that have examined performance of the same subjects across tasks (for reviews and examples, see Bryden, 1965; Dagenbach, 1986; Hellige, 1993a; Hellige, Bloch, & Taylor, 1988; Krutsch & McKeever, 1990; Nestor & Safer, 1990; see also Boles, 1989, 1991, 1992). This pattern of results is also consistent with the fact that studies of brain-injured patients have suggested that complementary hemispheric asymmetry for language and spatial functions exists only as a statistical norm rather than because of some causal connection (e.g., Bryden, 1982; Bryden, Hécaen, & De Agostini, 1983). It should be noted that the absence of larger correlations in Table 5 cannot be attributed completely to unreliability of the individual laterality scores, which typically show test–retest correlations ranging from about .60 to .90. In fact, in other studies in our laboratory that have examined test–retest correlations for some of the specific measures shown in Table 5, the correlations have fallen in this range. For example, for the specific auditory laterality measure used here, Hellige and Wong (1983) reported a test–retest correlation of approximately .60 averaged across three experiments. For the specific free-vision face task used here, Hellige, Cherry, and McDowd (1993) reported a test–retest correlation of .80, and for the CVC laterality score they reported a test–retest correlation of .67. In addition, the measures included in Table 5 all have proven sufficiently reliable to produce consistent effects across a number of experiments conducted by different investigators and in different laboratories.

The fact that laterality measures obtained from the different tasks correlate weakly or not at all has several interesting implications. For some time, a primary theoretical goal of research on hemispheric asymmetry was to discover the fundamental information-processing dimension along which the hemispheres differ and from which all of the various behavioral asymmetries might be derived (for discussion, see Bradshaw, 1989; Bradshaw & Nettleton, 1983; Bryden, 1982; Hellige, 1990, 1993a; see also Boles, 1991, 1992). At various times, the fundamental dimension has been characterized in different ways; for example, verbal versus nonverbal, analytic versus holistic, focal versus diffuse, and so on. To the extent that there is a single fundamental dichotomy of this sort, individual variation in performance asymmetry would reflect the fact that some individuals are more functionally asymmetric than others with respect to the critical information processing dimension. If the same fundamental dimension underlies all functional hemispheric asymmetries, then an individual who is strongly asymmetric for one task should be strongly asymmetric for others as well. When laterality indexes are computed in the manner described for Table 5, the asymmetries for two tasks that show the same direction of hemispheric dominance should correlate positively, and the asymmetries for two tasks that show the opposite direction of hemispheric dominance should correlate negatively. As a general rule, this specific pattern of positive and negative correlations is not found in Table 5. Consequently, the present results argue against the possibility that all functional hemispheric asymmetries can be reduced to a single fundamental dimension of the types that have been proposed and also argue against the notion that individual subjects can be simply characterized as strongly or weakly lateralized.

The results shown in Table 5 also are inconsistent with what has been termed the *hemisphericity* view of individual variation (e.g., Boles, 1991, 1992; see also Hellige, 1993a; Kim & Levine, 1991; Kim et al., 1990; Nestor & Safer, 1990). According to this view, individual variation in performance asymmetry reflects consistent biases toward one side of space or toward the use of one hemisphere—regardless of the specific task being performed. To the extent that this is the case, the correlations shown in Table 5 should be uniformly significant and positive (at least across Indexes 1 through 6, which measure performance differences between the hemispheres). The correlations shown in Table 5 clearly deviate from this expected pattern.

Thus far, we have noted certain general implications of the fact that most of the correlations shown in Table 5 are not significantly different from 0. The fact that this rules out certain very simple views of individual variation should not obscure the fact that the omnibus test leads to the clear rejection of a model with all of the correlations constrained to be equal to 0. As shown in Table 5, there are three theoretically interesting correlations that merit additional consideration.

As might be expected on the basis of previous results, the ear difference in dichotic listening (Index 1 in Table 5) did in fact correlate significantly with the left versus right visual field difference for total errors made during the CVC identification task (Index 6 in Table 5). The correlation was significant when all subjects were considered and for left-handers alone but not for right-handers. Furthermore, the correlation coefficient was significantly larger for left-handers than for right-handers, $z = 2.99$, $p < .01$.

To explore this relationship between ear and visual field differences in more detail, right- and left-handers were separated into those whose ear difference scores were at the extreme ends of their respective distributions. Specifically, subjects were chosen whose right − left ear scores were at least 1 standard deviation above or below the mean score of their handedness group. This resulted in 9 right-handers and 11 left-handers who showed a left-ear advantage (LEA group) and 8 right-handers and 10 left-handers who showed the largest right-ear advantage (large-REA group). Figure 4 shows the mean CVC laterality score (Index 6 in Table 5) for right- and left-handers in the LEA and large-REA groups. The CVC laterality scores were used in an ANOVA in which handedness and ear advantage group were between-subjects variables. As the data in Figure 4 suggest, the CVC laterality scores were significantly larger (indicating a greater RVF/LH advantage for CVC identification) in the large-REA group than in the LEA group, $F(1, 34) = 5.52$, $MS_e = 59.524$, $p < .025$. There was also a significant interaction of handedness and ear advantage group, $F(1, 34) = 4.29$, $MS_e = 59.524$, $p < .05$. As suggested by Figure 4, this interaction reflects the fact that the difference between the LEA and large-REA groups was significant for left-handers but not for right-handers. At least part of the difference between right- and left-handers may be attributable to the fact that both the ear difference scores and CVC laterality scores were more variable for left-handers than for right-handers.

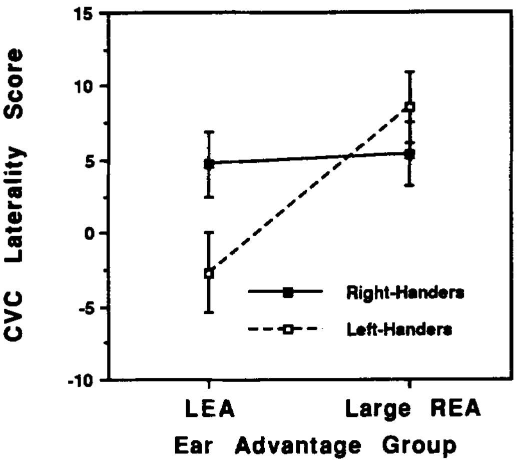

Figure 4. Consonant–vowel–consonant (CVC) laterality scores for right-handed and left-handed subjects who fell into each of the ear advantage groups: left-ear advantage (LEA) and large right-ear advantage (REA). Error bars show the standard errors of the mean scores.

As we discussed earlier, the fact that subjects who showed larger right-ear advantages in dichotic listening tended to show larger RVF/LH advantages during the CVC identification task makes a certain amount of intuitive sense, given that both tasks produce a right-side (left-hemisphere) advantage, and would appear to involve similar aspects of phonetic processing. Significant correlations of a similar sort have also been reported by Dagenbach (1986) for left-handed ($r = .26$) and ambidextrous subjects ($r = .20$) but not for right-handed subjects ($r = -.08$) in an experiment that included a dichotic word identification task and a visual CVC identification task similar to that used in Experiment 4. Using auditory and visual tasks that both required digit identification, Hines and Satz (1974) also found some evidence of cross-modal correlations of asymmetry, but their correlations were significant only for right-handers ($r = .39$) and when both right- and left-handers were considered together ($r = .27$) but not when left-handers were considered alone ($r = .02$). Small but significant cross-modal correlations of asymmetry have also been reported for both right-handers ($r = .28$) and left-handers ($r = .26$) by Krutsch and McKeever (1990), who used two versions of an object-naming latency task. Given the small size of these correlations even when they are statistically significant, it is not surprising that significant cross-modal correlations are not always found, even when similar tasks are used in both modalities (e.g., Bryden, 1965; Smith & Moscovitch, 1979; Zurif & Bryden, 1969). Taken together, these results suggest that, given sufficient reliability and similarity of auditory and visual tasks, there is a relationship between the asymmetries measured in the different modalities. That relationship can be quite dramatic for subjects whose asymmetry scores are at the extremes (see Figure 4). When the entire range of performance asymmetries is considered, however, the relationship is generally quite small.

The ear difference in dichotic listening (Index 1 in Table 5) also correlates significantly with the CVC bias score

(Index 8 in Table 8), and the correlation coefficients were not significantly different for right-handers versus left-handers. Recall that, the larger the CVC bias score, the more the qualitative error pattern on bilateral trials during the CVC identification task is like the pattern obtained on RVF/LH trials and different from the pattern obtained on LVF/RH trials. As the correlation indicates, larger values of the CVC bias score were associated with larger right-ear advantages in dichotic listening.

This relationship can be seen in Figure 5, in which the mean CVC bias scores are plotted for right- and left-handers who fell into the LEA and large-REA groups described earlier. As the data in Figure 5 suggest, the mean CVC bias score for the large-REA group was significantly larger than that for the LEA group, $F(1, 34) = 9.98$, $MS_e = .049$, $p < .005$. As also suggested in Figure 5, there was no interaction of handedness and ear advantage group, as the effect of ear advantage group was statistically significant for both right-handers and left-handers. Furthermore, in the LEA groups, the CVC bias score was negative for 16 of the 20 subjects, whereas in the large-REA groups, the CVC bias score was negative for only 5 of the 18 subjects.

One interpretation of this relationship is that subjects who are less left-hemisphere dominant (or even right-hemisphere dominant) for the sort of phonetic processing measured by the dichotic listening task are more likely than others to rely on right-hemisphere strategies for processing visually presented CVCs on redundant bilateral trials. An alternative interpretation is that both ear differences and choice of strategy on redundant bilateral trials are influenced by consistent perceptual biases toward one side of space or the other, which may be the product of an arousal asymmetry in favor of one hemisphere over the other (e.g., Levy, 1983; Levy et al., 1983a, 1993b; Hellige, Bloch, & Taylor, 1988; Kim & Levine, 1991; Kim et al., 1990). This possibility is interesting, because both the dichotic listening task and the bilateral trials of the CVC task present stimuli simultaneously to the two sides of space and as a consequence might be more sensitive to a consistent perceptual bias than would the unilateral trials of the CVC task. An interpretation in terms of this sort of perceptual bias might explain why the CVC bias score was not related to the unilateral visual field difference in overall error rate for the CVC task (Index 6 in Table 5). It must be noted, however, that asymmetry on the free-vision face task (Index 2 in Table 5) did not correlate with either the ear difference score (see also Hellige, Bloch, & Taylor, 1988) or with the CVC bias score. This is relevant because it has been argued elsewhere that asymmetry on the free-vision face task is influenced by characteristic perceptual bias (e.g., Levy et al., 1983a, 1983b; Kim et al., 1990), though it is also influenced by the extent to which the right hemisphere is dominant for the processing of emotions shown on faces.

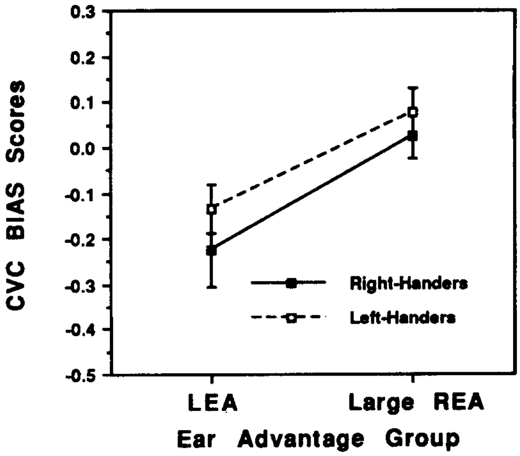

Figure 5. Consonant–vowel–consonant (CVC) bias scores for right-handed and left-handed subjects who fell into each of the ear advantage groups: left-ear advantage (LEA), large right-ear advantage (REA). Error bars show the standard errors of the mean scores.

The only additional significant relationship shown in Table 5 is the negative correlation between the visual field difference in QE scores (Index 7 in Table 5) and the CVC bias score (Index 8 in Table 5). This correlation is statistically significant in the data for all subjects combined, the data for right-handers and the data for left-handers—though the correlation is significantly larger for left-handers than for right-handers, $z = 3.05$, $p < .01$. To the extent that the QE score is larger on LVF/RH trials than on RVF/LH trials, the error pattern on redundant bilateral trials is more similar to the error pattern on LVF/RH trials than to the error pattern on RVF/LH trials. Given that some of the same values are used in the computation of both of these indexes, this relationship must be treated with some degree of caution. It may indicate, however, that the tendency to use a slower, letter-by-letter processing strategy on bilateral trials is greater to the extent that subjects are limited to such a strategy on LVF/RH trials. Although speculative, this possibility is consistent with the suggestion made elsewhere that the mode of CVC processing favored by the right hemisphere dominates on bilateral trials because a letter-by-letter mode of processing can be used by both hemispheres, whereas a more phonetic mode of processing would be restricted to the left hemisphere (e.g., Hellige, 1993a, 1993b; Hellige et al., 1989, in press).

Concluding Discussion

Individual differences in hemispheric asymmetry have often been discussed as though there were only one important dimension along which individuals can differ. In fact, there are likely to be a number of important dimensions of what might be termed *hemispheric asymmetry*, and individual variation on one dimension may or may not be related to individual variation on the others. Previous research has suggested that important dimensions include such things as the direction and magnitude of hemispheric superiorities for specific components of information processing, the direction and magnitude of arousal differences between the hemispheres, and various aspects of interhemispheric communication and coordination. In some studies, individual differences have been demonstrated by comparing groups that differ on such traits as handedness, sex, and familial sinistrality. In other studies, individual variation has been examined by comparing the task performance of specific individuals with one another, looking at consistency of asymmetry across time and across tasks. In the present study, we combined both approaches, because the pattern of consistency across tasks can shed light on the nature of group differences.

A general pattern that emerges across the present experiments is that functional hemispheric asymmetries are in the same direction for right- and left-handed groups, but the average size of the performance asymmetry is typically smaller for left-handed groups than for right-handed groups. As noted earlier, this general pattern of results is entirely consistent with previous studies that have examined the relationship of handedness to hemispheric asymmetry. It is tempting to conclude from this pattern of results that a typical left-handed individual is less strongly lateralized in general than is a typical right-handed individual. In fact, as long as different samples of left- and right-handed subjects are used in the various experiments, there is little evidence to rule out this sort of conclusion. According to this view, however, the same individuals who show a relatively large hemispheric asymmetry in the prototypical direction for one task should show a relatively large hemispheric asymmetry in the prototypical direction for other tasks. By including the same left- and right-handed subjects in each of our experiments, we were able to determine that this is not always the case. Among other things, this demonstrates what a multitask approach can contribute to understanding group differences in asymmetry.

The existence of a relationship between handedness and various aspects of functional hemispheric asymmetry has been acknowledged for some time. Not surprisingly, a number of genetic and environmental variables have been hypothesized to influence both handedness and hemispheric dominance for processing language (for examples, reviews, and discussion, see Annett, 1985; Bradshaw, 1989; Corballis, 1991; Coren, 1992; Geschwind & Galaburda, 1987; Hellige, 1993a, 1994; McManus & Bryden, 1993; Previc, 1991). According to many of these models, the same mechanisms that cause a shift away from right-handedness are also proposed to cause a shift away from left-hemisphere dominance for producing and perceiving speech. It is for this reason that such models are able to predict a relationship between handedness and various measures of left-hemisphere dominance for speech and language. To the extent that these models deal at all with the tendency for handedness to be related to various nonverbal hemispheric asymmetries, they typically imply or state explicitly that other types of asymmetry are reduced in left-handers as a byproduct of the reduced lateralization for language. This implies that asymmetry for language-related tasks (e.g., the ear difference in dichotic listening obtained in Experiment 1) should be correlated with asymmetries obtained in various nonverbal tasks (e.g., asymmetry obtained for the face-processing task in Experiment 2). The absence of such correlations in the present study and in other recent studies suggests that such models must be expanded to consider mechanisms by which handedness is related to a number of independent functional asymmetries.

More generally, the pattern of correlations (and lack of correlations) among various functional hemispheric asymmetries sheds light on which asymmetries might share a common genetic or developmental history or be related to the same underlying computational asymmetry. Although the present results have been useful for testing a small set of specific hypotheses about relationships among tasks, many more tasks must be examined in even larger sample sizes before we can make definitive statements about such things as the developmental history of hemispheric asymmetry. Although none of the studies to date has been sufficiently comprehensive to accomplish this, it is instructive to compare certain aspects of the present results with the results of an interesting series of experiments reported by Boles (1989, 1991, 1992).

By combining data from various experiments, Boles (1992) was able to examine the performance of right-handers on approximately 20 different tasks that show reliable functional asymmetries. On the basis of a series of factor analyses involving the asymmetry scores obtained from these tasks, he infers as many as nine different asymmetry "factors." Although none of the tasks used in the present experiments was identical to tasks used by Boles, some seem sufficiently similar to suggest the factors to which they might have contributed. For example, Boles included three dichotic listening tasks that involved the identification of spoken words or digits and found them to define a factor that he referred to as *auditory lexical.* Although the dichotic CV identification task we used in our Experiment 1 did not use lexical stimuli, it seems likely that auditory CV identification shares at least some processes with auditory word identification. Boles also included a free-vision face task very similar to that used in our Experiment 2 and found it to load on a factor he referred to as *facial figural.* A task that required subjects to localize a dot in space defined a factor that Boles referred to as *spatial positional.* Given that Boles' dot-localization task produced a reliable LVF/RH advantage, it would seem to involve some of the same spatial processes as the Near–Far task in our Experiment 3. Boles also included several visual half-field tasks using verbal stimuli such as printed numbers and words and found them to define a factor he referred to as *visual lexical.* Although the visual CVC identification task used in our Experiment 4 did not use lexical items, it is likely to share some processes with these tasks used by Boles.

Unfortunately, Boles (1991, 1992) did not report the correlations among the asymmetry scores obtained from his various tasks, so it is difficult to make a direct comparison with the present results. Nevertheless, the tasks used in the present experiments would be likely to load on different asymmetry factors as defined by Boles. This seems consistent with the fact that the asymmetries found with our various tasks are generally independent of each other—especially for the right-handed subjects, who would be most similar to the subjects used by Boles. All of this is complicated, however, by the fact that some of the derived factors identified by Boles are correlated with each other, and without new multitask studies it is difficult to tell whether or not the present results are inconsistent with some of those correlations.

The present results, combined with those of previous studies, do make it clear that ear differences in the identification of phonetic material are related to at least some phonetic or language-related asymmetries outside of the auditory modality. In the present study this is reflected in the correlation between ear asymmetry and visual field differences in the overall error rate during the CVC identification task. As noted earlier, similar relationships between the asymmetries obtained from auditory and visual tasks have been reported by others. Whether or not there is such a cross-modal correlation in a specific case is likely to depend on the extent to which the auditory and visual tasks require similar phonetic or language-related processes. In the various studies that have included both right- and left-handed subjects, the cross-modal correlation has sometimes been significant for one group but not for the other. For example, in the present study this correlation was significantly positive for the left-handed group but not for the right-handed group (see also Figure 4 and results reported by Dagenbach, 1986), but the opposite has also been reported (e.g., Hines & Satz, 1974). Because the various studies have not used exactly the same tasks, it could be that the pattern of intertask relationships is different in complex ways for right-handed groups versus left-handed groups. However, given the small size of the significant correlations, it is also possible that whether the correlation is significant in a particular sample depends on whether the range of asymmetries is sufficiently great for both the auditory and visual tasks. For example, in the present study the range of both ear asymmetries during the dichotic listening task and visual field asymmetry in the tachistoscopic task is smaller for the right-handed group than for the left-handed group. This would, of course, make it more difficult for a relationship between the tasks to be discovered in the data of the right-handed group.

The ear difference obtained using the CV identification task of Experiment 1 is also related to the CVC bias score obtained from Experiment 4. Recall that this score indicates the extent to which the qualitative pattern of errors obtained on bilateral trials during the CVC identification task is more similar to the LVF/RH or RVF/LH error pattern. It has been suggested elsewhere that the error pattern on bilateral trials provides information about what some have termed *metacontrol*—the tendency for one hemisphere (or the processing strategy associated with one hemisphere) to dominate when the conditions of perceptual stimulation do not favor one side or the other (e.g., Hellige, 1987, 1991, 1993a, 1993b, 1994, in press; Hellige et al., 1989, Hellige, Jonsson, & Michimata, 1988; Levy & Trevarthen, 1976). Thus, individual variation in the CVC bias score might reflect individual variation in this type of metacontrol. From this perspective, it is interesting that the CVC bias score was related to the ear advantage in dichotic listening. The existence of such relationships suggests that individuals do, in fact, differ in the extent to which the strategy used on bilateral trials is more similar to that used on LVF/RH versus RVF/LH trials. Although this is true with respect to CVC identification, additional multitask experiments are needed to determine whether it is also true of other tasks, whether individual variation in the direction of metacontrol for one task is related to individual variation in the direction of metacontrol for other tasks, and whether variation in metacontrol is related to other aspects of interhemispheric collaboration.

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