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Individual Differences in the Hemispheric Specialization of Dual Route Variables

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The dual route model suggests that reading of letter strings can occur through both a lexical and a nonlexical route. Hemispheric specialization of these routes has also been posited, suggesting that the left hemisphere has both lexical and nonlexical routes while the right hemisphere has only a lexical route. However, some recent data conflict with this hemispheric dual route model, suggesting that both hemispheres may have access to both routes. The purpose of the present study was to investigate individual differences in the hemispheric specialization of these routes and to determine whether these group differences in their specialization might explain conflicts in the literature. The effect of four individual difference factors was explored: handedness, biological sex, menstrual stage (i.e., fluctuations in estrogen), and self-rated degree of masculinity (i.e., sexual attribution). We looked at the interaction of these individual differences with the following dual route variables: (i) string length, (ii) word frequency, (iii) regularity of grapheme–phoneme correspondences of words, and (iv) the interaction of frequency and regularity using a bilateral lexical decision task. We observed that sex, menstrual stage, and masculinity each affected hemispheric specialization of the dual route variables, but did so in different ways. We posit that both hemispheres have orthographical (lexical) access as well as phonological (nonlexical) access to words. Further, we suggest that the presence of phonological processing in the right hemisphere depends on available resources and the strategies used, which are subject to individual differences.

INTRODUCTION

It is generally believed that the left cerebral hemisphere is specialized for processing natural language, but the extent of the right hemisphere involve-

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ment in language processing is controversial. In order to sharpen the question, we restrict attention to word recognition and ask whether the right hemisphere contributes selectively to orthographic as against phonological processing of printed words. The dual route model suggests that reading of letter strings can occur through two separate routes, a lexical route and a nonlexical route. These distinct routes were posited partly to explain the human ability to read aloud both exception words (via the lexical route) and nonwords (via the nonlexical route). Both routes start with a visual analysis system that assigns abstract letter identities and positions to the letters in the input string. The lexical route proceeds from (i) a visual lexicon to (ii) a semantic storage to (iii) an addressed phonological encoding to (iv) articulation and speech. The nonlexical route, on the other hand, proceeds from (i) a grapheme-to-phoneme conversion to (ii) an assembled phonology and then (like the lexical route) to (iii) articulation and speech. It has been hypothesized that while each hemisphere can store abstract letter identities (Eviatar & Zaidel, 1994, 1995; Zaidel, 1998) and use its own lexical route, only the left hemisphere has access to a nonlexical route. Modularity of the two routes in the two hemispheres is usually assumed to abide by the following characteristics: (i) the lexical and nonlexical routes in the left hemisphere do not interact, (ii) the lexical routes in the two hemispheres do not interact, and (iii) the lexical route is faster than the nonlexical route.

While results from brain-damaged populations have provided considerable support for these assertions, recent studies (Iacoboni & Zaidel, 1996; Zaidel, 1998) do not support the major tennets of the hemispheric version of the dual route model. In numerous studies, we have consistently found that (i) all dual route model variables can affect performance, but none are necessary in any condition. (ii) Effects only emerge when the system is taxed. In particular, (iii) regularity effects are seen in both visual fields (VFs), suggesting that the right hemisphere does have access to a nonlexical route. (iv) Length effects occur in both VFs and can occur both for words and for nonwords. However, if they occur for words then they also occur for nonwords and if they occur in the right VF (RVF) than they also occur in the left VF (LVF) (Eviatar & Zaidel, 1991; and see review of this topic in Zaidel, 1998). It is generally believed that (i) frequency effects index lexical route processing, (ii) regularity effects index nonlexical route processing, and (iii) length effects index the visual analysis system common to both routes and also possibly grapheme-to-phoneme translation in the nonlexical route. Finally, the existence of two separable routes predicts an interaction between frequency and regularity, such that regularity effects should be prominent for low frequency words.

One possibility for the discrepancy between the results on which the original hemispheric specialization version of the dual route model is based and those presented here may involve individual differences in the sample populations used. For instance, it is possible that males, especially those with greater hemispheric specialization for language, might be more likely to show hemisphere-dependent, dual route variable effects than would females, especially those with less hemispheric specialization for language. Likewise, the average right hander might be expected to show greater hemispheric specialization than would the average left hander. Differences in biological sex and handedness are most often used for studying group differences in hemispheric specialization, but recent work also suggests that subjects might differ in their hemispheric specialization and callosal connectivity based on their self-rated masculinity and level of both stable and fluctuating steroid hormone levels (see Weekes & Zaidel, 1995; Weekes, 1996, for a review of this work).

Indeed, there has been direct support in the literature for the idea that the strength and hemispheric specialization of these dual route variables show dramatic individual differences. In a recent paper, Pugh and colleagues (1997) tested the hypothesis that the strength of the effects of dual route variables might be determined by specific asymmetries in regional brain activation and that these asymmetries are subject to individual differences. The researchers present behavioral and neuroimaging data supporting a connection between the extent to which an individual demonstrates effects of phonological regularity and length (in free vision) and the extent to which (s)he shows bilateral PET activation of the inferior frontal gyrus. Of central interest, a sex difference was found in both measures. (i) Females, but not males, showed regularity effects on a lexical decision task, and (ii) females showed greater bilateral activation of the inferior frontal gyrus than did males. Since both sex and bilateral activation were found to predict regularity (and, therefore, phonological) effects, Pugh and colleagues performed a regression analysis and found that the brain activation variable accounted for 10% more of the behavioral variance than did the sex variable (36 and 26%, respectively), suggesting that the extent to which a particular dual route variable impacts performance is, indeed, predicted by the strength of regional brain activation observed.

The purpose of the present study was to investigate individual differences in the magnitude and hemispheric specialization of dual route model variables and whether they explain discrepancies in the literature. We focus specifically on the effects of (i) word regularity, (ii) word frequency, (iii) the interaction of these two factors, and (iv) word and nonword length on performance patterns using a bilateral lexical decision task. We expect greater hemispheric differences in males than in females on these dual route model variables, as well as greater evidence for a nonlexical route in the right hemisphere of females. This prediction is based on previous studies of individual differences in perceptual asymmetries, showing that females have more bilaterally represented language ability. Evidence from other studies suggests that highly masculinized females and females tested during the high estrogen, midluteal stage of the menstrual cycle may also show patterns of greater hemispheric specialization (Weekes, 1996; Weekes & Zaidel, 1996).

Data from three separate experiments will be presented here. The first experiment investigated biological sex, the second experiment investigated the separate and combined effects of biological sex and handedness, and the third experiment investigated the separate and combined effects of menstrual stage and self-rated masculinity.

METHODS

Subjects

In the first experiment, 24 UCLA undergraduate students (12 males, 12 females) served as subjects. All were strongly right-handed with no first-degree left-handed relatives. Subjects were also all native English speaking.

In the second experiment, 41 UCLA undergraduate students served as subjects. Twenty-four were right-handed (10 males, 14 females) and seventeen were left-handed (8 males, 9 females). Subjects were also all native English speaking.

In the third experiment, 32 normally menstruating females from the greater UCLA community served as subjects. Sixteen of the subjects were in the high estrogen, midluteal stage of the menstrual cycle and 16 were in the low estrogen menses stage of the menstrual cycle during testing. All subjects had to meet strict inclusion criteria involving their hormonal history (see below).

Procedures

Subjects in all three studies were first asked to provide written informed consent. Subjects in the third study were given a number of questionnaires and a battery of neuropsychological tests. The questionnaires included the Bem Sex Role Inventory (BSRI; Bem, 1974), which requires subjects to rate themselves on 20 stereotypically masculine, 20 stereotypically feminine, and 20 stereotypically neutral items. The menstrual cycle of each prospective subject was tracked for 3 months prior to that subject being admitted for behavioral testing. Inclusionary criteria for these subjects were that each: (i) be between 20 and 35 years of age, (ii) have regular menstrual cycles (i.e., between 25 and 35 days each month, with no more than a 2-day variability across months for any single subject), (iii) have menses stages (i.e., periods) ranging from 4 to 7 days (not varying more than 1 day for any single subject), and (iv) have no history of oral contraceptive use in the 6 months prior to beginning tracking nor incidence of pregnancy in the 12-month period prior to testing. Subjects were randomly assigned to begin testing during either the high estrogen (midluteal) or low estrogen (menses) stage in the cycle. The midluteal stage of the cycle was determined using Asso's (1983) phase-length estimates. Validity of the midluteal stage was accomplished through follow-up phone calls on the first or second day of the next menses. Only the data from women whose ''midluteal'' testing occurred within 5 to 10 days before the onset of menstruation were included in the analyses.

Subjects in all three experiments were then given a bilateral lexical decision task, which required them to determine whether a cued, lateralized target letter string was a word or a nonword (see Iacoboni & Zaidel, 1996, for a detailed discussion of the task). In the first (biological sex) and third (sexual attribution and menstrual stage) experiments, lateralized targets occurred with word or nonword distractors in the other VF (bilateral presentations) or alone (unilateral presentations). The second experiment (biological sex and handedness) contained only bilateral trials. All three experiments used stimuli from the same word and nonword sets, although the second study used only a subset of the words used by the first and third studies. Study two used three-, four-, and five-letter words and categorized word stimuli into two levels: regular and irregular. The first and third study, on the other hand, used three-, four-, five-, and six-letter words and categorized word stimuli into three levels: regular, irregular, and rule bound. This third level of regularity was used to denote words which were not pronounced using the established grapheme-to-phoneme correspondence but for which a rule was well established (Seymour et al., 1992).

Data Analysis

Meta-analyses were performed using data combining the Iacoboni and Zaidel (1996) population with the two new populations presented here. Four sets of analysis of variance (ANOVA) with repeated measures were performed, using percentage errors and median reaction time as the dependent variables. These separate ANOVAs were run in order to assure sufficient cell size. The first set of analyses (I) investigates the effects of frequency on word trials. The second set of analyses (II) investigates the effects of regularity on word trials. The third set of analyses (III) investigates the effects of the interaction of frequency and regularity on word trials. Finally, the fourth set of analyses (IV) investigates the effects of length on word and nonword trial performance.

The meta-analysis was undertaken to establish the laterality of dual route variables in our whole population and to ascertain that the experiments are well behaved. The data from the three separate populations were then analyzed, using the four sets of ANOVAs described above, specifically to investigate the effects of the following individual difference variables: (a) biological sex from the data of Iacoboni and Zaidel (1996), (b) biological sex and handedness in the second study, and (c) menstrual stage and masculinity in the third study. In each case, two ANOVAs were run (one for accuracy and one for median reaction time).

In order to keep the data included in the meta-analyses of the three experiments as consistent as possible, only results from the left and right hand blocks of the Iacoboni and Zaidel experiment have been included in this paper. These results, however, do not differ significantly from when bimanual blocks were also included in the analyses (see Iacoboni & Zaidel, 1996). Further, given that one of the experiments contained only bilateral trials while the other two contained a mixture of bilateral and unilateral trials, unilateral trials were also removed from the meta-analyses.

We will present the data as follows. First the two meta-analyses are presented. Then for each of the four sets of analyses (one for each dual route variable), the results from each of the three experiments will be presented. For instance, within the ''frequency'' analyses, we will present one accuracy and one median reaction time analysis for (i) biological sex, (ii) biological sex and handedness, and (iii) menstrual stage and masculinity.

RESULTS

Meta-analysis

A meta-analysis across the three experiments revealed the following significant effects which involved interaction of dual route variables and visual field of target. First, there was a significant interaction in accuracy between VF and Frequency [$F(1, 79) = 8.16$; $p < .006$], such that the LVF showed a greater frequency effect (with high frequency words more accurate than low frequency words) than did the RVF (see Fig. 1). Second, there was a significant interaction between Visual Field and Regularity [$F(1, 79) = 8.08$; $p < .006$] in reaction time, such that the LVF showed a regularity effect while the RVF did not (see Fig. 2). However, the three-way interaction between Visual Field, Frequency, and Regularity predicted by the hemispheric

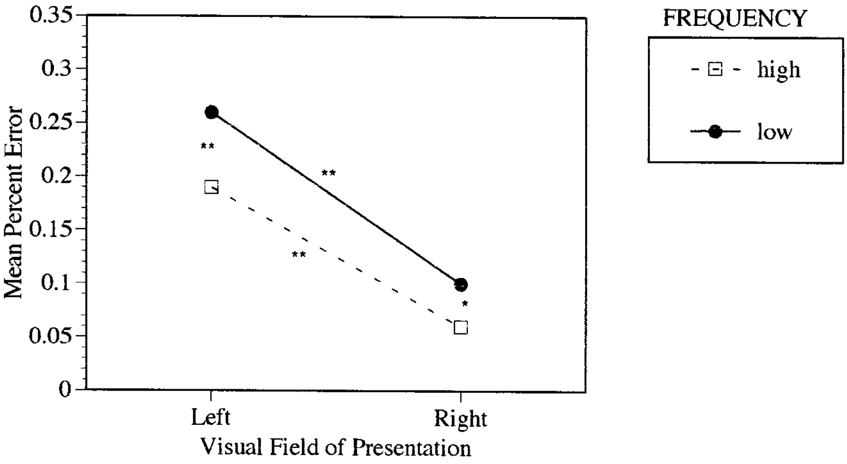

FIG. 1. The interaction between Visual Field and Frequency in the meta-analysis.

version of the dual route model was not significant with either dependent variable. Third, there was a significant three-way interaction in accuracy between Visual Field, Wordness, and Length [$F(2, 158) = 10.82$; $p < .0001$], such that decisions of RVF words did not show a length effect while decisions of RVF nonwords and both LVF words and LVF nonwords were affected by length (see Fig. 3). Similarly, this interaction between Visual Field, Wordness, and Length proved significant in the median reaction time measure [$F(2, 158) = 3.16$; $p < .0001$] (see Fig. 4). Again, RVF words were the only trials not to show a length effect across experiments. With few

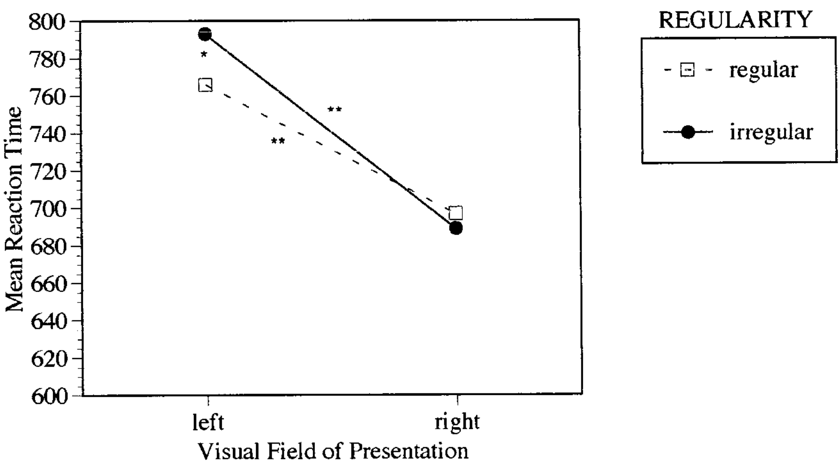

FIG. 2. The interaction between Visual Field and Regularity in the meta-analysis.

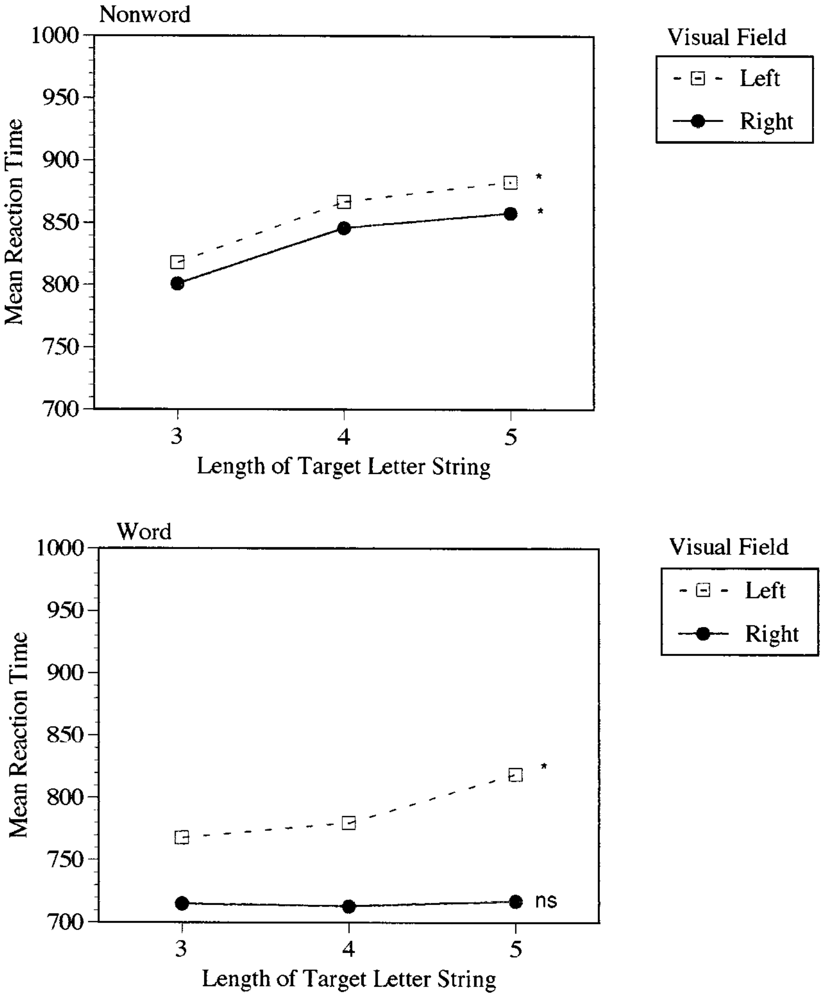

FIG. 3. The interaction between Visual Field, Target Wordness, and Length (reaction time) in the meta-analysis.

exceptions, these four interactions were also found to be significant in the separate ANOVAs for each experiment.

Meta-analyses were also performed using median splits to distinguish fast and slow responders (for analyses with median reaction time as the dependent variable) and to distinguish more and less accurate responders (for analyses with accuracy as the dependent variable). The analyses demonstrated a significant interaction between Visual Field and Latency Level [$F(1, 78) = 10.00$; $p < .002$] and between Visual Field and Accuracy Level [$F(1, 78) = 33.30$; $p < .0001$], such that slower and less accurate subjects showed

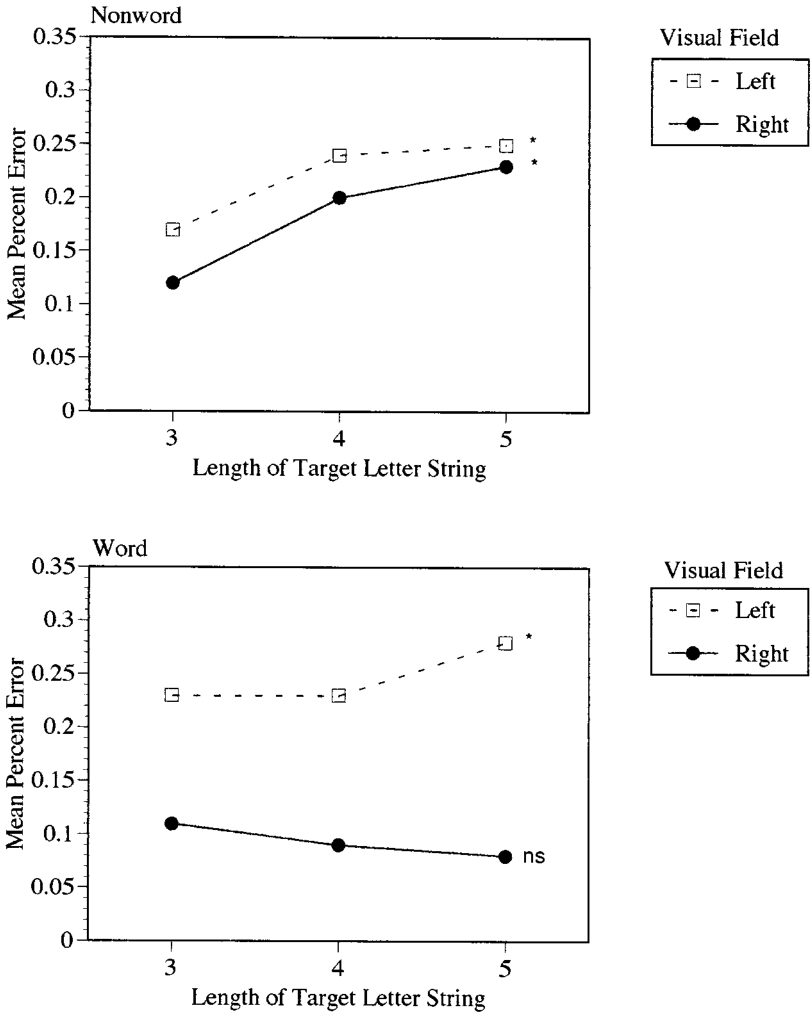

FIG. 4. The interaction between Visual Field, Target Wordness, and Length (accuracy) in the meta-analysis.

a greater RVFA than did faster and more accurate subjects. This was due mostly to poorer performance in the LVF by the slow subjects and by the less accurate subjects. There were also significant interactions between Frequency and Latency Level [$F(1, 78) = 6.17$; $p < .02$] and between Frequency and Accuracy Level [$F(1, 78) = 8.16$; $p < .006$], such that slower and less accurate subjects showed greater frequency effects due exclusively to poorer performance on low frequency words.

In the following ANOVAs for the separate experiments, we will emphasize those effects or interactions which either (i) were not mentioned in the meta-analysis or (ii) were modified by the between-subject variables.

Word Frequency

The Influence of Sex on Word Frequency Effects

The analysis included Visual Field (left, right), Presentation (bilateral, unilateral), and Frequency (high, low) of word targets as within-subject factors. Sex (female, male) served as a between-subject factor.

Accuracy. The analysis revealed main effects of Sex [$F(1, 22) = 4.10$, $p < .0551$] such that females were more accurate than were males (proportion correct .85 vs. .80), of Visual Field [$F(1, 22) = 65.65$, $p < .0001$] such that RVF trials were more accurate than were LVF trials (.92 vs. .72), of Presentation [$F(1, 22) = 45.10$, $p < .0001$] such that unilateral trials were more accurate than were bilateral trials (.87 vs. .78), and of Frequency [$F(1, 22) = 10.62$, $p < .004$] such that high frequency words were more accurate than were low frequency words (.84 vs. .81).

A significant interaction between Visual Field and Presentation [$F(1, 22) = 11.09$, $p < .003$] was also observed such that there was a larger RVFA for bilateral than for unilateral trials (−.16 and −.09, respectively). No other interactions reached significance. In particular, the Visual Field by Frequency effect which was observed in the meta-analysis was not significant here.

There were no significant interactions involving Sex.

Median latency. The significant main effects and interactions reported for accuracy were also significant for reaction time.

There were no significant effects involving Sex.

The Influence of Sex and Handedness on Word Frequency Effects

The analysis included Visual Field (left, right) and Frequency (high, low) of Word targets as within-subject factors. Sex (female, male) and Handedness (left handers or Lh, right handers or Rh) served as between-subject factors.

Accuracy. The analysis revealed main effects of Sex [$F(1, 37) = 5.63$, $p < .0230$], of Visual Field [$F(1, 37) = 28.65$, $p < .0001$], and of Frequency [$F(1, 37) = 97.32$, $p < .0001$], such that (i) females were more accurate than were males (.85 vs. .77), (ii) RVF trials were more accurate than were LVF trials (.88 vs. .75), and (iii) high frequency words were more accurate than were low frequency words (.86 vs. .76).

A significant interaction between Visual Field and Frequency [$F(1, 37) = 9.72$, $p < .0035$] was also observed such that LVF trials elicited a frequency effect whereas RVF trials did not.

There was also a significant interaction between Visual Field and Sex

[$F(1, 37) = 5.07$, $p < .0303$], such that males showed a significantly larger RVFA than did females, due to significantly lower LVF scores. There were no significant effects involving Handedness nor significant interactions with sex and handedness.

Median latency. The significant main effects reported for accuracy were also significant for reaction time, as was the interaction between Visual Field and Frequency [$F(1, 37) = 9.78$, $p < .0034$].

There were no significant interactions involving either Sex or Handedness, nor involving the interaction between sex and handedness.

The Influence of Menstrual Stage and Masculinity on Word Frequency Effects

The analysis included Visual Field (left, right), Presentation (bilateral, unilateral) and Frequency (high, low) of Word targets as within-subject factors. Masculinity (high, low) and Menstrual Group (menses, midluteal) served as between-subject factors.

Accuracy. The analysis revealed significant main effects of Visual Field [$F(1, 28) = 56.09$, $p < .0001$], of Presentation [$F(1, 28) = 28.71$, $p < .0001$], and of Word Frequency [$F(1, 28) = 8.05$, $p < .008$] in the same direction as was described under The Influence of Sex on Word Frequency Effects.

Significant interactions were observed between Visual Field and Presentation [$F(1, 28) = 29.01$, $p < .0001$] and between Visual Field and Frequency [$F(1, 28) = 8.41$, $p < .007$]. The first interaction reflects the fact that there was a greater right visual field advantage for bilateral than for unilateral trials. The second interaction occurred because of a significantly larger frequency effect in the LVF than in the RVF ($p < .0001$).

Regarding the effects of the between-subject factors, there was a significant interaction between Visual Field, Frequency, and Menstrual Group [$F(1, 28) = 8.40$, $p < .007$], such that the menses group showed a greater RVFA for low frequency words than for high frequency words due to significantly worse performance of low frequency words relative to high frequency words in the LVF. The midluteal group, on the other hand, showed equivalent RVFAs across levels of word frequency. This effect was further modified by a significant four-way interaction between Visual Field, Presentation, Frequency, and Menstrual Group [$F(1, 28) = 4.09$, $p < .0529$], such that the increase in RVFA for low frequency words in the menses group was only true for bilateral trials. For unilateral trials, both menstrual groups showed equivalent RVFAs across frequency assignments (see Fig. 5).

Median latency. The analysis revealed significant main effects of Masculinity [$F(1, 28) = 4.79$, $p < .04$], of Visual Field [$F(1, 28) = 29.01$, $p < .0001$], of Presentation [$F(1, 28) = 68.78$, $p < .0001$], and of Word Fre-

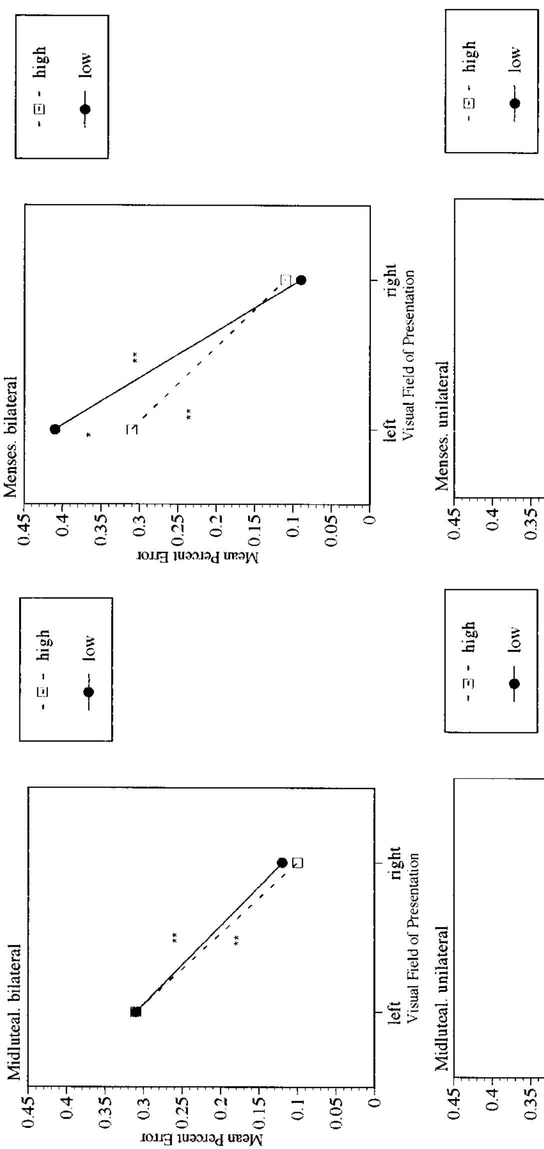

FIG. 5. The interaction between Visual Field, Frequency, Presentation, and Menstrual Stage in Experiment 3.

quency [$F(1, 28) = 17.37$, $p < .0003$], with high masculine women responding faster than low masculine women, RVF trials being responded to faster than LVF trials, unilateral trials faster than bilateral trials, and high frequency words faster than low frequency words.

There were no other effects involving either Masculinity or Menstrual Group.

Word Regularity

The Influence of Sex on Word Regularity Effects

The analysis included Visual Field (left, right), Presentation (bilateral, unilateral), and Regularity of Word (regular, irregular) as within-subject factors. Sex (female, male) served as a between-subject factor.

Accuracy. The analysis revealed main effects of Visual Field [$F(1, 22) = 65.09$, $p < .0001$] and of Presentation [$F(1, 22) = 46.29$, $p < .0001$], similar to that seen in the frequency analyses.

A significant interaction was observed between Visual Field and Presentation [$F(1, 22) = 10.80$, $p < .0034$], again similar to that seen in the frequency analyses.

A significant interaction between Presentation, Regularity, and Sex [$F(1, 22) = 4.32$, $p < .0208$] was also observed, such that females demonstrated significantly worse performance on irregular words in the bilateral trials and males demonstrated significantly worse performance on regular words in the bilateral trials (see Fig. 6).

Median latency. The analysis revealed main effects of Visual Field [$F(1, 22) = 41.75$, $p < .0001$] and of Presentation [$F(1, 22) = 48.50$, $p < .0001$].

Significant interactions were also found between Visual Field and Presentation [$F(1, 22) = 4.18$, $p < .0530$] and between Visual Field and Regularity [$F(1, 22) = 3.15$, $p < .0526$], the first of which was described above. This second interaction reflects greater laterality for irregular words than for regular words, due to significantly faster LVF responses for irregular words than for regular words.

The Influence of Sex and Handedness on Word Regularity Effects

The analysis included Visual Field (left, right) and Regularity of Word (regular, irregular) as within-subject factors. Sex (females, males) and Handedness (Lh, Rh) served as between-subject factors.

Accuracy. The analysis revealed a main effect of Visual Field [$F(1, 37) = 170.54$, $p < .0005$].

There was a significant interaction between Regularity and Handedness [$F(1, 37) = 4.35$, $p < .01$], such that right handers showed greater regularity effects than did left handers. There were no other effects involving handedness and regularity and there were no main effects or interactions including

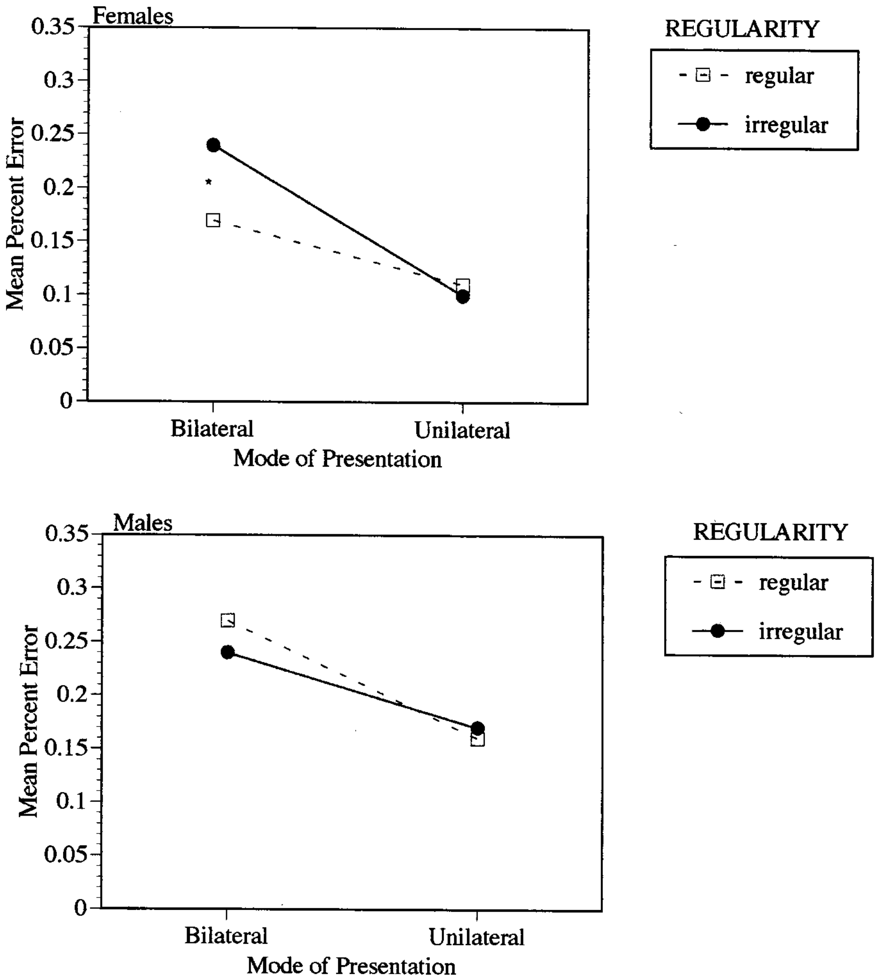

FIG. 6. The interaction between Presentation, Regularity, and Sex in Experiment 1.

Sex as a factor. Specifically, there was no interaction between Sex, Regularity and Visual Field.

Median latency. The analysis revealed a main effect of Visual Field [$F(1, 37) = 14.57$, $p < .0005$].

A significant interaction between Visual Field, Regularity, and Sex [$F(1, 37) = 4.31$, $p < .0449$] occurred, such that females showed a RVFA for regular but not for irregular words. Males, on the other hand, showed similar and significant RVFAs for both levels of Regularity (see Fig. 7).

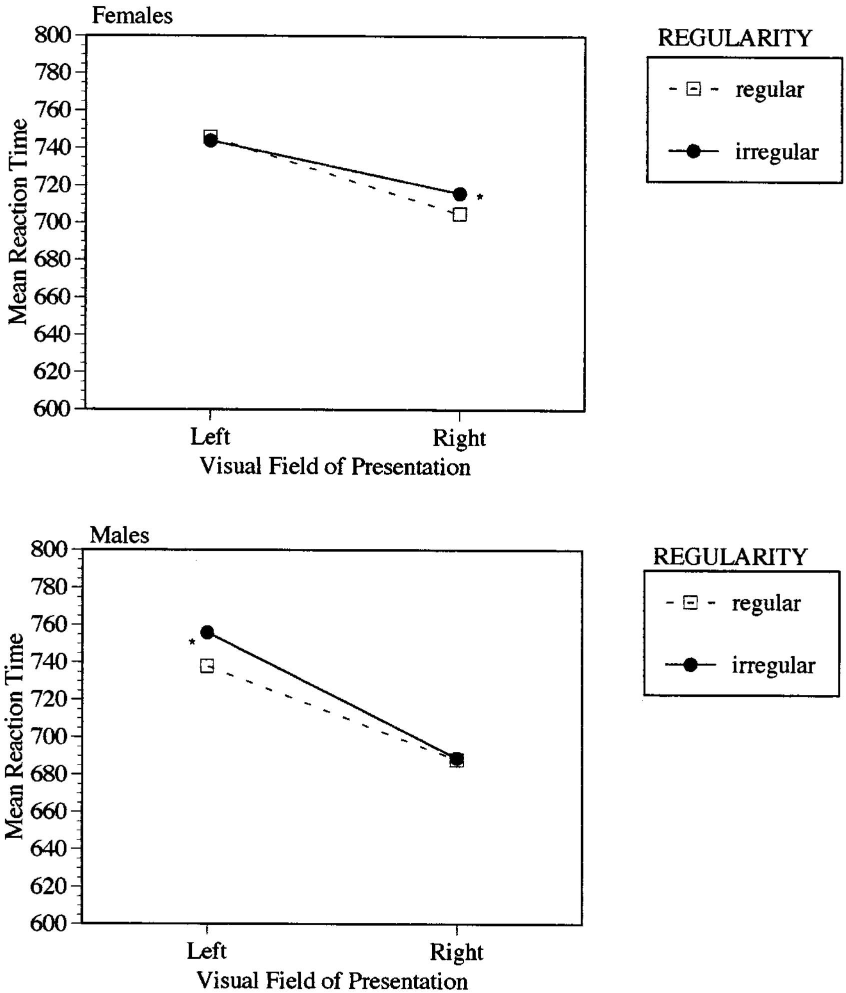

FIG. 7. The interaction between Visual Field, Regularity, and Sex in Experiment 2.

The Influence of Menstrual Stage and Masculinity on Word Regularity Effects

The analysis included Visual Field (left, right), Presentation (bilateral, unilateral), and Regularity of Word (regular, irregular) as within-subject factors. Menstrual Stage (midluteal, menses) and Masculinity (high, low) served as between-subject factors.

Accuracy. The analysis revealed main effects of Visual Field [$F(1, 28) = 56.01$, $p < .0001$] and of Presentation [$F(1, 28) = 28.81$, $p < .0001$]. A significant interaction was found between Visual Field and Presentation

[$F(1, 28) = 11.07$, $p < .0025$]. All of these effects have also been described above.

There were no significant effects involving the two between-subject factors.

Median latency. The analysis revealed main effects of Visual Field [$F(1, 28) = 23.03$, $p < .0001$], of Presentation [$F(1, 28) = 62.48$, $p < .0001$], of Regularity [$F(1, 28) = 6.59$, $p < .0027$], and of Masculinity [$F(1, 28) = 4.33$, $p < .0467$].

A significant interaction was also observed between Visual Field and Regularity [$F(1, 28) = 6.88$, $p < .0021$], such that in the LVF regular words were responded to more quickly than were irregular words, whereas no effect of Regularity was found for RVF trials. There was also a trend toward a significant interaction between Presentation and Regularity [$F(1, 28) = 2.93$, $p < .0614$], such that in the unilateral trials, regular words were responded to slightly more quickly than were irregular words, whereas no effect of Regularity was found for bilateral trials.

There were no significant effects involving the two between-subject factors.

Frequency × Regularity

The Influence of Sex on the Interaction between Frequency and Regularity of Words

Accuracy. There were no significant interactions involving Frequency and Regularity.

Latency. There were no significant interactions involving Frequency and Regularity.

The Influence of Sex and Handedness on the Interaction between Frequency and Regularity of Words

Accuracy. There was a significant interaction between Frequency and Regularity [$F(1, 37) = 14.57$, $p < .0005$], such that only low frequency words showed an effect of Regularity.

There were no significant interactions between Frequency and Regularity that were further modified by Sex or Handedness.

Median latency. There were no significant interactions involving Frequency and Regularity.

The Influence of Menstrual Stage and Masculinity on the Interaction between Frequency and Regularity of Words

Accuracy. There were no significant interactions involving Frequency and Regularity.

Latency. There were no significant interactions involving Frequency and Regularity.

String Length

The Influence of Sex on Length Effects

The analysis included Visual Field (left, right), Wordness (nonword, word), and Length (three, four, five, and six letters) as within-subject factors. Sex (male, female) served as a between-subject factor.

Accuracy. The analysis revealed main effects of Visual Field [$F(1, 22) = 74.50$, $p < .0001$], of Wordness [$F(1, 22) = 7.98$, $p < .0098$] and of Length [$F(3, 66) = 26.38$, $p < .0001$].

Significant interactions were observed between Visual Field and Wordness [$F(1, 22) = 35.10$, $p < .0001$] and between Visual Field and Length [$F(3, 66) = 3.32$, $p < .0251$]. These two-way interactions were further modified by a significant three-way interaction between Visual Field, Wordness, and Length [$F(3, 66) = 5.58$, $p < .0018$], such that RVF words did not show a length effect while RVF nonwords and both LVF words and LVF nonwords were affected by length. There were no effects involving Sex, Length, and Visual Field.

Median latency. The analysis revealed main effects of Visual Field [$F(1, 22) = 16.88$, $p < .0001$], of Wordness [$F(1, 22) = 77.63$, $p < .0001$], and of Length [$F(3, 66) = 14.87$, $p < .0001$]. Significant interactions were observed between Visual Field and Wordness [$F(1, 22) = 33.58$, $p < .0001$] and between Wordness and Length [$F(3, 66) = 2.89$, $p < .0418$]. These two-way interactions were further modified by a three-way interaction between Visual Field, Wordness, and Length [$F(3, 66) = 2.73$, $p < .0509$], showing the same pattern as was discussed for accuracy.

With regard to Sex, there was a significant two-way interaction between Sex and Length [$F(3, 66) = 4.48$, $p < .0064$], which was further modified by a significant three-way interaction between Sex, Visual Field, and Length [$F(3, 66) = 4.48$, $p < .0064$] (see Fig. 8), such that females show greater lateral differentiation than do males. There were no effects involving Sex, Length, and Visual Field.

The Influence of Sex and Handedness on Length Effects

The analysis included Visual Field (left, right), Wordness (nonword, word), and Length (three, four, and five letters) as within-subject factors. Sex (female, male) and Handedness (Lh, Rh) served as between-subject factors.

Accuracy. The analysis revealed main effects of Sex [$F(1, 37) = 5.35$, $p < .0264$], of Visual Field [$F(1, 37) = 23.14$, $p < .0001$], and of Length [$F(1, 37) = 14.54$, $p < .0001$]. A trend toward significance was also observed for the main effect of Wordness [$F(1, 37) = 3.53$, $p < .0684$].

There were significant interactions between Visual Field and Wordness [$F(1, 37) = 24.84$, $p < .0001$], as well as between Visual Field, Length, and Wordness [$F(1, 37) = 24.84$, $p < .0001$]. There were no interactions involving Sex or Handedness, Length, and Visual Field.

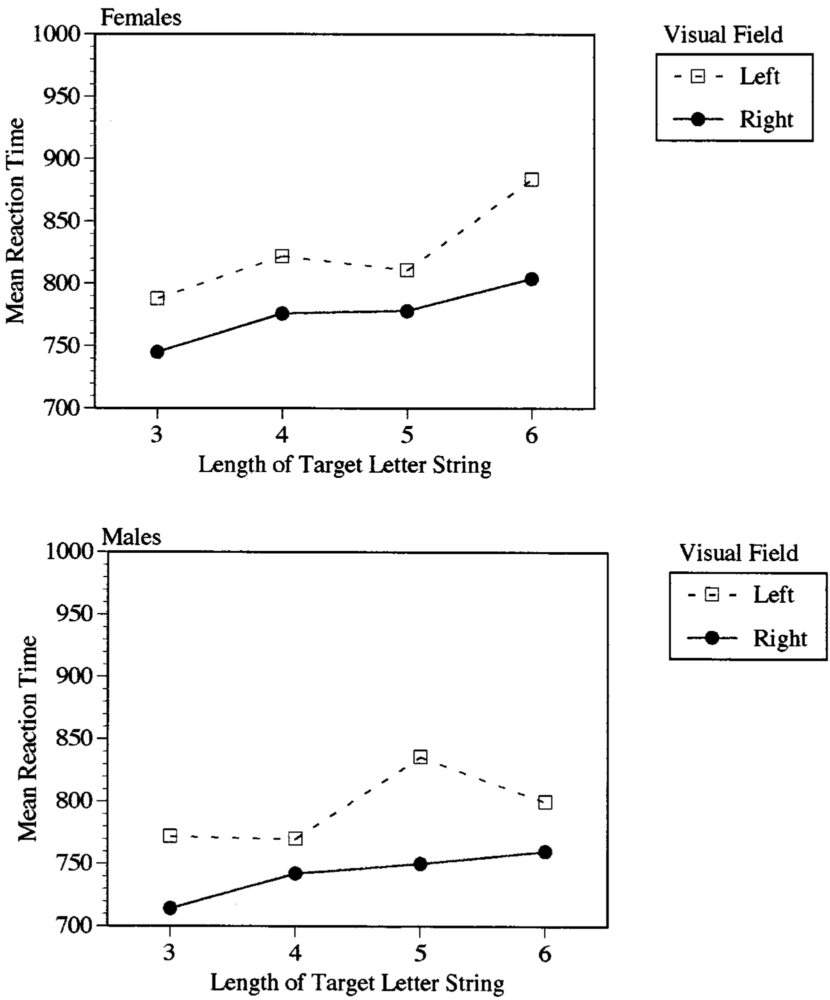

FIG. 8. The interaction between Visual Field, Regularity, and Sex in Experiment 2.

The Influence of Menstrual Stage and Masculinity on Length Effects

The analysis included Visual Field (left, right), Wordness (nonword, word), and Length (three, four, five, and six letters) as within-subject factors. Menstrual Stage (midluteal, menses) and Masculinity (high, low) served as between-subject factors.

Accuracy. The analysis revealed main effects of Visual Field [$F(1, 28) = 53.64, p < .0001$], of Wordness [$F(1, 28) = 6.61, p < .0157$], and of Length [$F(3, 84) = 33.30, p < .0001$].

Significant interactions between Visual Field and Wordness [$F(1, 28) =$

26.40, $p < .0001$], Wordness and Length [$F(1, 28) = 3.04$, $p < .0333$], and Visual Field, Wordness, and Length [$F(1, 28) = 12.99$, $p < .0001$] were also observed as before.

There were no significant effects involving the two between-subject factors.

Median latency. The analysis revealed main effects of Visual Field [$F(1, 28) = 26.23$, $p < .0001$], of Length [$F(3, 84) = 15.47$, $p < .0001$], and of Masculinity [$F(1, 28) = 6.41$, $p < .0172$].

Significant interactions between Visual Field and Wordness [$F(1, 28) = 17.88$, $p < .0002$], and Visual Field, Wordness, and Length [$F(1, 28) = 6.13$, $p < .0008$] were also observed, with the same patterns as discussed above.

Regarding the between-subject factors, there was a significant interaction between Visual Field, Wordness, Length, and Masculinity [$F(1, 28) = 2.79$, $p < .0457$], such that high masculine females showed different interactions between Wordness and Length in the two Visual Fields, whereas the low masculine females did not (see Fig. 9).

DISCUSSION

The purpose of this experiment was to investigate individual differences in hemispheric specialization for processing dual route variables in word recognition. Three consistent hemispheric effects emerged across experiments. First, as may be expected, the right hemisphere was more sensitive to variations in frequency than was the left hemisphere. Second, surprisingly, the right hemisphere was also more sensitive to variations in regularity than was the left hemisphere. Finally, length effects were evident for both words and nonwords in the right hemisphere but only for nonwords in the left hemisphere, confirming previous observations (e.g., Eviatar & Zaidel, 1991).

These general effects were further modified by all three sex-related, individual difference variables investigated here (see Table 1). First, biological sex affected both regularity and length. Specifically, while both males and females showed effects of regularity on bilateral but not unilateral trials, females demonstrated significantly worse performance to irregular words while males demonstrated worse performance to regular words in this condition. Further, this sex difference in regularity was significant in the right hemisphere but not in the left hemisphere. With regard to length, females showed greater hemispheric specialization for length effects than did males. Furthermore, females showed the greatest decline in right hemisphere performance from five- to six-letter strings, whereas males showed the greatest decline in performance in the right hemisphere from four- to five-letter strings. Regarding the effects of menstrual stage, the low estrogen, menses group but not the high estrogen, midluteal group showed greater frequency effects in the right hemisphere than in the left hemisphere. Finally, high

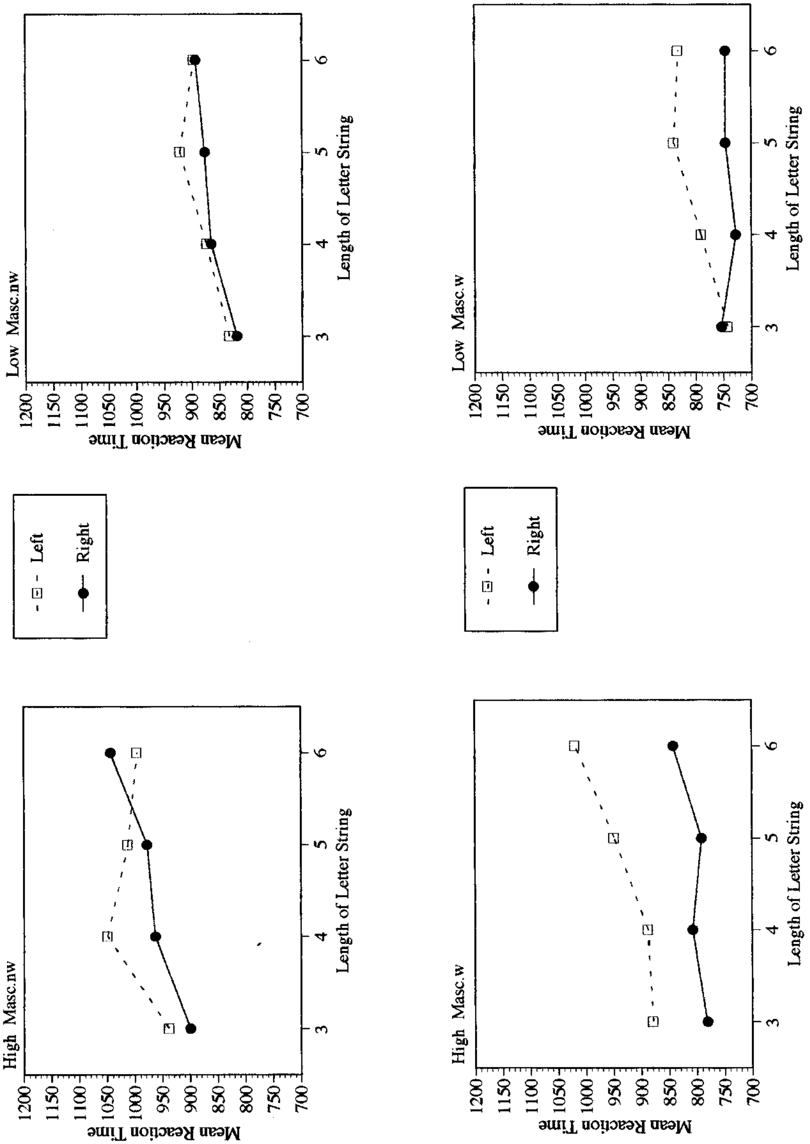

FIG. 9. The interaction between Visual Field, Length, Target Wordness, and Masculinity in Experiment 3.

TABLE 1
The Interactions between Visual Field (Hemispheric Specialization), the Dual Route Variables, and the Individual Difference Factors

Interaction	Sex (Expt 1)	Sex (Expt 2)	Handedness	Menstrual stage	Masculinity
VF × Frequency	—	—	—	*Menses > Midluteal (Bi)	—
VF × Regularity	—	Females (RVF)/ males (LVF)	—	—	—
VF × Frequency × Regularity	—	—	—	—	—
VF × Length	Females > males	—	—	—	High masculine > low masculine

Note. Bi, effect only occurred in the bilateral trials; Females (RVF)/males (LVF), females demonstrated a regularity effect in the right visual field (RVF), whereas males demonstrated a regularity effect in the left visual field (LVF).

masculine females demonstrated greater hemispheric specialization regarding the interaction between length and wordness than did the low masculine group.

Two general facts about the bilateral lexical decision paradigm might help us better interpret the effects of dual route model variables. First, results from this task consistently demonstrate (i) an interaction between the visual field of target (stimulus) presentation and the wordness of the target, as well as (ii) a less frequent interaction between hand of response and visual field of target presentation. These interactions suggests that each hemisphere is processing the stimuli which project directly to it in a direct-access fashion (see Zaidel, 1983; and Zaidel, Clarke, & Suyenobu, 1990, for reviews of this topic). Second, there is a consistent interaction between visual field of presentation and presentation mode (i.e., unilateral vs. bilateral presentation). The pattern of this interaction suggests that bilateral trials enhance perceptual asymmetries, presumably by increasing the independence of the two hemispheres (Boles, 1987; Iacoboni & Zaidel, 1996; Rayman & Zaidel, 1991). Given the direct-access explanation of the processing of stimuli in this paradigm, the fact that both frequency and regularity effects were stronger across experiments for LVF rather than for RVF trials implies that the right hemisphere is more sensitive to these two dual route variables. Furthermore, the fact that sex differences occurred in the LVF rather than the RVF suggests that the right hemisphere is also more sensitive to individual differences.

Consider more closely the effects of biological sex on dual route variables. Although this is controversial (e.g., Zaidel et al., 1995), the majority of studies finding differences in perceptual asymmetries between men and women suggest that men are more lateralized than are women. This is supported by results both in normal subjects (see Bryden, 1988, for a review) and in brain-damaged populations (see Kimura & Hampson, 1994; Weekes, 1996, for reviews). The strongest and most consistent effects appear to be in dichotic listening (e.g., Harshman, 1991; Harshmann & Hampson, 1987) with far less evidence for sexual differentiation being reported in lateralized tachistoscopic tasks such as lexical decision. The fact that females were found to be more laterally differentiated in the present study may suggest that the inconsistency of effects in previous studies may reflect different patterns of sex differences on different linguistic variables.

Consider next the effects of menstrual stage on dual route variables. Estrogen fluctuations across the menstrual cycle have been shown to affect hemispheric specialization of both verbal and nonverbal tasks. What is still debated is whether the effect of activational steroid concentrations is greater on the specialization of a particular task or on the extent to which specific channels of the corpus callosum are involved in transferring or inhibiting information during processing. Although the original theories of Hampson and Kimura (e.g., Hampson & Kimura, 1988; Kimura & Hampson, 1994) emphasized the role of enhanced estrogen in activating the left hemisphere, more recent studies have suggested a role for estrogen in inhibiting the right hemisphere (Mead & Hampson, 1997) or in inhibiting callosal interaction (Weekes, 1996; Weekes & Zaidel, 1996). What to make then of the selective effect of word frequency in the right hemisphere of the menses group in the bilateral presentation condition, where a distractor stimulus is projected to the left hemisphere?

The low estrogen in the menses group might influence behavior by affecting (i) callosal connectivity or (ii) the efficiency of the right hemisphere's lexical and nonlexical routes. Numerous experiments strongly suggest that bilateral presentation of stimuli interferes with callosal transfer and encourages processing by direct access (Boles, 1983, 1987; Iacoboni & Zaidel, 1995; Rayman & Zaidel, 1991). If the performance of the two menstrual groups on LVF trials differed only in the unilateral trials, this could be partly evidence for the menses group having impaired callosal connectivity. Instead, we found the groups to differ only in the case when callosal transfer is already suppressed by experimental conditions (i.e., with bilateral presentations). This result strongly implies that the low estrogen levels of the menses group reduce the right hemisphere's linguistic capacity. Further, the fact that low frequency words were affected most suggests that it is the nonlexical route in the right hemisphere which gets inhibited.

As we have discussed, there is evidence suggesting greater hemispheric specialization in males than in females on both verbal and nonverbal tasks. Far fewer studies have investigated the extent to which sex role attribution (i.e., degree of masculinity and of femininity) may also impact lateral differentiation. Nonetheless, there is some indication that sexual attribution affects laterality differently than does biological sex or menstrual stage. For instance, Weekes, Zaidel, and Zaidel (1995) reported greater right ear advantages in high masculine males than in low masculine males. A larger study (Weekes & Zaidel, 1996) found the effect to also be significant in females.

Further, Berfield, Ray, and Newcombe (1986) found that high masculine males showed more lateralized EEG patterns in response to a mental rotation task than did low masculine males, whereas high feminine females showed more bilateral patterns than did low feminine females. The present study's focus on masculinity reflects the mounting evidence that it is more predictive of performance patterns than is femininity. This was also confirmed by our own preliminary analyses, where we found that high masculine females showed greater laterality than did low masculine females whether or not their femininity scores were high or low. Again, we find greater laterality in high masculine than in low masculine females.

Another individual difference factor which impacted performance in the present study was the overall skill level of the subject. Those subjects who were slower and/or less accurate than the median subject showed (i) greater RVFA for the task (due primarily to significantly lower performance in the LVF-RH) and (ii) greater effects of frequency (due primarily to significantly lower performance on infrequent stimuli). Both of these patterns are of great interest and deserve further investigation. The greater RVFA in low performers suggests that increased difficulty in lexical decision results from deficits in the right (nondominant) rather than the left (dominant) hemisphere. Further, the fact that frequency (but not regularity or length) was impacted by overall performance also suggests a deficit in the lexical rather than the nonlexical route of the right hemisphere.

The emergence of an effect of a dual route variable in a given visual field appears to depend on the paucity of processing resources in that hemisphere. It would appear that both hemispheres have access to both routes but that the right hemisphere has more limited resources and is therefore more likely to exhibit effects of dual route variables. The consistent finding that dual route variables have a greater effect on performance in the right hemisphere (for all subjects, but most especially for slow and inaccurate subjects) suggests that the right hemisphere linguistic system is a more labile, less important, backup processor.

To summarize, in the present study, individual differences in hemispheric specialization of dual route variables were investigated. The results suggest that biological sex, menstrual stage, and masculinity each affect the hemispheric specialization of the dual route variables, but do so in different ways. While sex affected both regularity and length, menstrual stage affected frequency and masculinity affected length. Further, females in general, as well as low estrogen and high masculine females, were found to have greater lateral differentiation for these dual route variables than did males and high estrogen and low masculine females, respectively. Surprisingly, handedness had no effect on hemispheric specialization for these dual route variables. Finally, the skill level of the subject was also found to impact hemispheric specialization of the task, such that those subjects with lower performance levels showed selective deficits in the right hemisphere.

As compelling as these findings are, they do not provide a concise explanation for the discrepancies in the literature regarding the hemispheric version of the dual route model. Instead, they provide further support for the fact that the right hemisphere has access to a nonlexical route just as does the left hemisphere. This finding varied little across either sex or handedness groups and suggests that the original model is in need of reformulation. Processing load, not hemisphere of presentation, appears to determine whether manipulations in dual route variables impact performance. Finally, this study suggests that group differences in resources and strategies should be considered explicitly as a revised model of dual route variable processing emerges.

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