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Cross-Language Tests of Hemispheric Strategies in Reading Nonwords

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Four experiments explored the effects of specific language characteristics on hemispheric functioning in reading nonwords using a lateralized trigram identification task. Previous research using nonsense consonant-vowel-consonant (CVC) trigrams has shown that total error scores reveal a right visual field (RVF) advantage in Hebrew, Japanese, and English. Qualitative error patterns have shown that the right hemisphere uses a sequential strategy, whereas the left hemisphere uses a more parallel strategy in English but shows the opposite pattern in Hebrew. Experiment 1 tested whether this is due to the test language or to the native language of the participants. Results showed that native language had a stronger effect on hemispheric strategies than test language. Experiment 2 showed that latency to target letters in the CVCs revealed the same asymmetry as qualitative errors for Hebrew speakers but not for English speakers and that exposure duration of the stimuli affected misses differentially according to letter position. Experiment 3 used number trigrams to equate reading conventions in the 2 languages. Qualitative error scores still revealed opposing asymmetry patterns. Experiments 1–3 used vertical presentations. Experiment 4 used horizontal presentation, which eliminated sequential processing in both hemispheres in Hebrew speakers, whereas English speakers still showed sequential processing in both hemispheres. Comparison of the 2 presentations suggests that stimulus arrangement affected qualitative errors in the left visual field but not the RVF for English speakers and in both visual fields for Hebrew speakers. It is suggested that these differences result from orthographic and morphological differences between the languages: Reading Hebrew requires attention to be deployed to all the constituents of the stimulus in parallel, whereas reading English allows sequential processing of the letters in both hemispheres. Implications of cross-language studies for models of hemispheric function are discussed.

The experiments described in this article focus on the effects of the characteristics of written language on the functioning of the cerebral hemispheres in a lateralized syllable identification task. Previous experiments using this paradigm in English with native English speakers have revealed a systematic and reliable pattern of performance asymmetry that has been interpreted as reflecting qualitative processing differences between the two hemispheres and has yielded insights into interhemispheric interaction when the stimuli are simultaneously available to both hemispheres (e.g., Eng & Hellige, 1994; Luh & Levy, 1995). Cross-language studies are important in this context because they provide generalizing power for theoretical models of hemispheric functioning. Such studies have revealed both universal patterns that are independent of language and effects that are specific to the characteristics of the languages studied. For example, it has been shown that the right visual field advantage (RVFA) for language tasks in lateralized paradigms is a reflection of left-hemisphere (LH) dominance for language irrespective of the characteristics of the particular language (e.g., Eviatar, 1996; Faust, Kravetz, & Babkoff, 1993; Poizner, Kaplan, Bellugi, & Padden, 1984; Vaid, 1988). It also has been shown that structures that are lexically or syntactically relevant in some languages, for example, pitch changes in tonal languages (Moen, 1993; Van Lancker & Fromkin, 1973) or spatial aspects of syntax in sign language (Poizner et al., 1984), are processed by the LH for speakers of those languages but not for speakers of languages in which these structures do not have linguistic meaning. In addition, cognitive habits related to language may affect lateralization of other processes, as reading scanning habits have been hypothesized to affect a variety of visual attentional processes, for example, the direction of illusory motion (Morikawa & McBeath, 1992) and the left preference for chimeric faces (Eviatar, 1997; Vaid & Singh, 1989).

It is important to note that although psycholinguistic studies of language processing have revealed both universal and language-specific patterns, the relevance of the results of lateralized studies to more general language processes is not straightforward. For example, Scott and Hellige (1998) recently showed that the ubiquitous word frequency by spelling regularity interaction in word naming does not show up with peripheral presentations. They suggested that performance of language tasks in which stimuli are presented in

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the peripheral visual fields may be qualitatively different from performance of such tasks when the stimuli are presented in central vision, as they are in most psycholinguistic tasks. However, lateralized cross-language tasks can speak to models of hemispheric function and can delimit the interaction of general universal attributes of hemispheric processes with the effects of specific learned behaviors. That was the goal of the present experiments.

The Paradigm

The experimental task consisted of presenting vertically oriented consonant–vowel–consonant (CVC) nonword trigrams by means of a divided visual field paradigm to the peripheral visual fields. The stimuli were presented unilaterally to the right visual field (RVF) and to the left visual field (LVF) and also bilaterally to both visual fields simultaneously (the BVF condition). Stimuli in the RVF were initially encoded by the LH, those in the LVF were initially available only to the right hemisphere (RH), and those in the BVF were available to both hemispheres simultaneously. The participants were asked to read the stimulus aloud and to identify its constituent letters. This task was developed by Levy, Heller, Banich, and Burton (1983) and has been used extensively by Hellige and his colleagues to explore both hemispheric functions and interhemispheric interaction (e.g., Hellige et al., 1994; Hellige, Taylor, & Eng, 1989). Processing of the stimuli was indexed by analyzing the number and types of errors made in each visual presentation condition. This task is especially useful because it yields several types of data. The percentage of errors in each visual field is an index of hemispheric specialization for the task, with the BVF condition revealing processing efficiency when both hemispheres have access to the stimulus. In addition, the types of errors made by the participants were analyzed as a qualitative index of the type of processing that occurred in each condition. The errors were classified into three categories: First errors (FEs) were defined as errors on the first letter of the CVC when the last letter was reported correctly (irrespective of the accuracy of the vowel). Last errors (LEs) were defined as errors on the last letter of the CVC when the first letter was reported correctly (again ignoring the correctness of the vowel). All other errors (e.g., errors only on the vowel or all three letters reported incorrectly) were classified as other errors (OEs). This classification was made separately for responses in each of the visual presentation conditions, and the data were normalized such that each error category represented the percentage of those types of errors in a particular visual field. This was done to clarify the error patterns because there was a consistent RVFA in errors for this linguistic task, whereas the measure of interest was the difference between the relative proportion of FEs and LEs in each of the visual fields. Previous studies using English (e.g., Hellige & Cowin, 1996; Hellige et al., 1989) have reported an asymmetry in this measure, indicating a larger difference between normalized FEs and LEs in the LVF (RH) than in the RVF (LH).

Hellige and his colleagues have mapped the extent of these effects in English in various ways. In general, their results can be summarized as follows: These asymmetries (i.e., larger differences between FEs and LEs in the LVF than in the RVF) are larger when the stimuli are pronounceable but still exist when they are not (Eng & Hellige, 1994; see also Kim, 1996). The asymmetries are due to retinal location, not to perceptual reference frame, because they do not occur when the stimuli are rotated 90° (Hellige, Cowin, Eng, & Sergent, 1991). The asymmetry does not depend on order of report because it occurs even when participants report the stimuli backward (last letter first; Hellige & Scott, 1997). Hellige and his colleagues interpreted these results as indicating several things about hemispheric functioning. First, when the stimuli are pronounceable, the LH uses a phonological strategy, whereas the RH uses a serial letter-by-letter strategy. Second, when the stimuli are not pronounceable, the FE–LE differences are due to hemispheric differences in the deployment of attention. Eng and Hellige (1994) invoked a hypothesis proposed by Reuter-Lorenz and Baynes (1992) that the hemispheres differ in their ability to process local elements in a multipart visual array. The idea is that the LH is better able to deploy attention in parallel over the elements of the array, which underlies the smaller difference in the RVF between FEs and LEs. Eng and Hellige suggested that the patterns in the qualitative errors in the two visual fields are due to a combination of these factors (LH parallel phonological processing vs. RH sequential letter-by-letter processing, and differential hemispheric abilities in local vs. global processing). Finally, attention in both visual fields is deployed top-to- bottom over these vertically presented stimuli, even when the response is required to be bottom-to-top.

Two studies conducted with languages other than English reported somewhat different results (Eviatar, 1996; Hellige & Yamauchi, 1999). Both studies reported quantitative patterns similar to English (an RVFA and a bilateral advantage) but a very different qualitative pattern. Hellige and Yamauchi presented trigrams constructed of Kana characters to native Japanese speakers and found no difference in the relative number of FEs and LEs in the two peripheral fields. I reported data from use of the paradigm in Hebrew (Eviatar, 1996)[1] and found that the qualitative error patterns in Hebrew and English were opposing. Native English speakers completing the task in English revealed the same pattern as that reported by Hellige and his colleagues (e.g., Hellige & Cowin, 1996)—namely, larger differences between FEs and LEs in the LVF than in the RVF—whereas native Hebrew speakers completing the task in Hebrew revealed the opposite pattern—namely, larger differences between FEs and LEs in the RVF than in the LVF. Thus, it seems as if the language of the test, the native language of the participants (Hebrew, Japanese, or English), or both affected hemispheric strategies in this task. Before describing the experiments, I briefly describe the orthographic and morphological characteristics of Hebrew.

[1] Sections of the data reported below appear in Eviatar (1996).

Orthography

In Hebrew, all verbs and most nouns are written primarily as consonantal roots that are differently affixed and voweled to form the words of the lexicon (Berman, 1978). Most written materials do not include vowels, although there are four letters in Hebrew that, in addition to their role in signifying specific consonants, also specify long vowels (these are called "matres lectionis"). However, in some cases it is difficult for the reader to determine whether these dual-function letters represent a vowel or a consonant. When vowels do appear (in poetry, children's books, and liturgical texts), they are signified by diacritical marks above, below, or within the body of the word. Inclusion of these marks completely specifies the phonological form of the orthographic string, making it completely transparent in terms of orthography–phonology relations. Because the majority of written materials do not include the diacritical marks, a single printed word not only is often ambiguous between different lexical items (this ambiguity is normally solved by semantic and syntactic processes in text comprehension) but also does not specify the phonological form of the letter string. Thus, in its unpointed form, Hebrew orthography contains very little vowel information and includes a large number of homographs. Hebrew is written from right to left. In all the present experiments, the stimuli were unvoweled; that is, they did not include diacritical marks that specified their pronunciation.

Morphology

The consonantal roots of Hebrew verbs and most nouns and adjectives are embedded in preexisting morphological word patterns to form specific words (Berman, 1978; Frost & Bentin, 1992). Only the combination of the abstract root and morphological pattern forms specific words. The root carries the core meaning of the words that are formed around it, whereas the form pattern indicates word class, tense, gender, and number. The letters that make up the root may be dispersed across the word, interdigitated with the matres lectionis and other consonants that belong to the morphological pattern. In English, multimorphemic words are usually created by affixation, in which the stem is usually a word itself, and its orthographic integrity is largely preserved. This difference may affect reading strategies, as Farid and Grainger (1996) showed that initial fixation position in a word results in somewhat different response patterns in French (which is similar to English in morphological structure and in reading direction) and in Arabic (which is similar to Hebrew in morphological structure and in reading direction). In French, fixation slightly to the left of the word's center results in the best recognition for both prefixed and suffixed words, whereas in Arabic, prefixed words result in the best recognition from leftward fixations, and suffixed words result in the best recognition from rightward initial fixations. They suggested that this is due to the greater importance of morphological structure in Arabic, because "much of the phonological representation of the word can be recovered only after successfully matching the consonant cluster to a lexical representation" (Farid & Grainger, 1996, p. 364), that is, after extraction of the root.

Thus, although both Hebrew and English are alphabetic orthographies, they differ in three major ways: reading direction (English is read left-to-right, whereas Hebrew is read right-to-left), orthography–phonology relations (phonological uncertainty in English arises mostly as a result of inconsistency of vowel pronunciations; in unvoweled Hebrew, it arises from the omission of vowels), and morphological structure (in English, the stem of a multimorphemic word is a word, and its orthographic integrity is usually preserved; in Hebrew, most words are at least bimorphemic and consist of an abstract root and a word form, with the orthographic integrity of the root often disrupted by the letters making up the word form). The present experiments examined the possible effects that these language differences have on the qualitative measures of hemispheric function in the CVC identification task.

Experiment 1: Native Language and the Language of the Test

Experiment 1 looked at the effects of the language of the test versus the native language of the participants on the qualitative error asymmetries in the CVC paradigm. That is, how much of the differences in qualitative patterns is due to the language of the test, and how much of it is due to long-term language habits that are specific to the native language of the participants? I explored these questions by having native Hebrew speakers and native English speakers complete the task in their native language and in their second language.

Method

Design

The CVC paradigm yielded two types of dependent variables. The first is total errors, which is the percentage of errors (out of 36) in each visual field. This measure indicates the quantitative differences between the visual presentation conditions. The qualitative error categories were calculated separately for each visual field as the number of each type of error (FE, LE, or OE) divided by the total number of errors in that visual field. The experiment used a mixed design. The quantitative analyses used three independent variables: Native language (Hebrew vs. English) and test language (Hebrew vs. English) were between-groups variables, and visual field (LVF, RVF, or BVF) was a within-groups variable. For the qualitative error analyses, the within-groups variable of error type (FE vs. LE) was added.

Participants

Eighty students participated in the experiment. Forty native Hebrew speakers were recruited from the participant pool of the Psychology Department at the University of Haifa. All were right-handed and neurologically normal and had learned English in grade school starting at Grade 4. They had not been exposed to any other language. Twenty students performed the task in Hebrew, and 20 students performed the task in English. Forty native English speakers were recruited from the Oversees Program at the University of Haifa. All were right-handed and neurologically normal and had begun participating in an intensive course in Hebrew at the time. Twenty students performed the task in English, and 20 students performed the task in Hebrew. The participants who performed the task in Hebrew were presented with an unvoweled paragraph in Hebrew taken from a fourth-grade reader. All of the participants who were included in the study were able to fluently read aloud the paragraph without errors. The native English speakers were paid 15NIS (an equivalent of $5) for their participation.[2]

Stimuli and Procedure

The stimuli in both language conditions were 37 vertically presented CVC trigrams created from a set of 15 letters. In English, the 1st and 3rd letters of the trigrams were chosen from a set of 12 consonants: *B, C, G, D, J, K, T, S, P, M, V,* and *Z*, and the 2nd letter was chosen from 3 vowels: *A, O,* and *E*. All were capital letters in Helvetica-Bold font in 16-point type. In Hebrew, the 1st and 3rd letters of the trigrams were chosen from the set: ת, פ, ס, מ, ל, כ, ע, ח, ד, ך, ג, and ב, and the 2nd letter was always י, ו, or א, which often double as vowels. The letters were in Maariv-B40 font in 18-point type. None of the trigrams in Hebrew included diacritical marks that could specify the form of the vowel. All of the letters subtended 0.5° × O.5° of visual angle. All stimuli were presented vertically, with their inner edge 1.5° of visual angle from fixation. The trigrams subtended 0.5° horizontally and 2° vertically. The experimental trials were presented in three blocks of 37 trials, in which the 1st trial was not scored. Across blocks, each item appeared once in each visual presentation condition. The order of the trials was pseudorandom, with the constraint that each presentation condition preceded the others an equal number of times. To achieve a 50% error rate, the exposure duration of the stimuli was titrated in 15-ms intervals after each trial. If the participant made an error, the next stimulus was shown for 15 ms longer. If the participant correctly reported all 3 letters, the exposure duration was titrated down by 15 ms. This computation was automated by the computer. The maximum exposure duration was 210 ms. The participant completed 37 trials as practice before beginning the experimental trials. The order of events on each trial was as follows: A 1000-Hz tone sounded to alert the participant that the trial was beginning, a fixation cross appeared for 2 s, and then the stimulus was shown for the appropriate duration. A bilateral pattern mask consisting of horizontal lines appeared for 200 ms immediately after the stimulus. The participant pronounced the syllable and then spelled it. The experimenter typed the participant's response into the computer, and after 2 s, the next trial began. The experiment was run on a Silicon Graphics workstation (Model Personal Iris 4D30), which also collected the responses.

Results

Exposure Duration

The titration of exposure durations to achieve an approximately 50% error rate was effective. Table 1 presents the total percentages of errors in each of the language conditions and also includes the average exposure durations needed by the participants to achieve this error rate. I analyzed the average exposure durations by using a two-way analysis of variance (ANOVA) with native language and test language as between-groups variables. The main effect of native language was significant, $F(1, 76) = 12.55$, $p < .001$. The main effect of test language was also significant, $F(1, 76) = 80.69$, $p < .001$, as was the interaction between native language and test language, $F(1, 76) = 131.84$, $p < .0001$. This interaction is shown in Table 1, in which it can be seen that when participants performed the task in their native language, Hebrew speakers required longer exposure durations than did English speakers for a 50% error rate, and English speakers doing the task in Hebrew had the highest error rate and needed the longest exposure duration. Presumably, this effect reflects the relative difficulty of the task for these individuals, because they were less familiar with Hebrew than were the Hebrew speakers with English.

Table 1
Average Percentages of Errors and Exposure Durations in the Language Conditions

	Native language			
	Hebrew		English	
Test language	% error	Exposure duration (in ms)	% error	Exposure duration (in ms)
Hebrew	49.5	76	61.8	188
English	49.4	95	42.6	36

Total Errors

The percentages of errors in each visual field in the four language conditions are presented in the top panel of Figure 1. It can be seen that all participants made fewer errors in the RVF than in the LVF (an RVFA) and even fewer errors in the BVF condition (a bilateral advantage). I analyzed these data by using a three-way ANOVA with native language (Hebrew vs. English) and test language (Hebrew vs. English) as between-groups variables and visual field (LVF, RVF, or BVF) as a within-subject variable. The three-way interaction was not significant ($p > .10$). Two 2-way interactions were significant: Test Language × Visual Field, $F(2, 152) = 4.64$, $p < .05$, with the Hebrew test resulting in a smaller RVFA (4.17%) and a larger bilateral advantage (9.58%) and the English test resulting in the opposite pattern (RVFA = 13.05% and bilateral advantage = 3.68%), and Native Language × Test Language, $F(1, 76) = 45.29$, $p < .0001$, with the language of the test not affecting the total errors of Hebrew speakers, whereas native English speakers made more errors on the Hebrew test than on the English test (see Table 1).

Planned comparisons revealed that the simple interaction of Test Language × Visual Field was not significant for Hebrew speakers ($p > .25$) because both groups showed an RVFA and a bilateral advantage. For English speakers, this simple interaction was significant, $F(2, 76) = 6.46$, $p < .005$, because they showed a stronger RVFA in English than in Hebrew. Analysis of the unilateral errors revealed that there was an effect of native language on the RVFA only

[2] Sections of the data from the native language conditions in this experiment were used by Eviatar (1996).

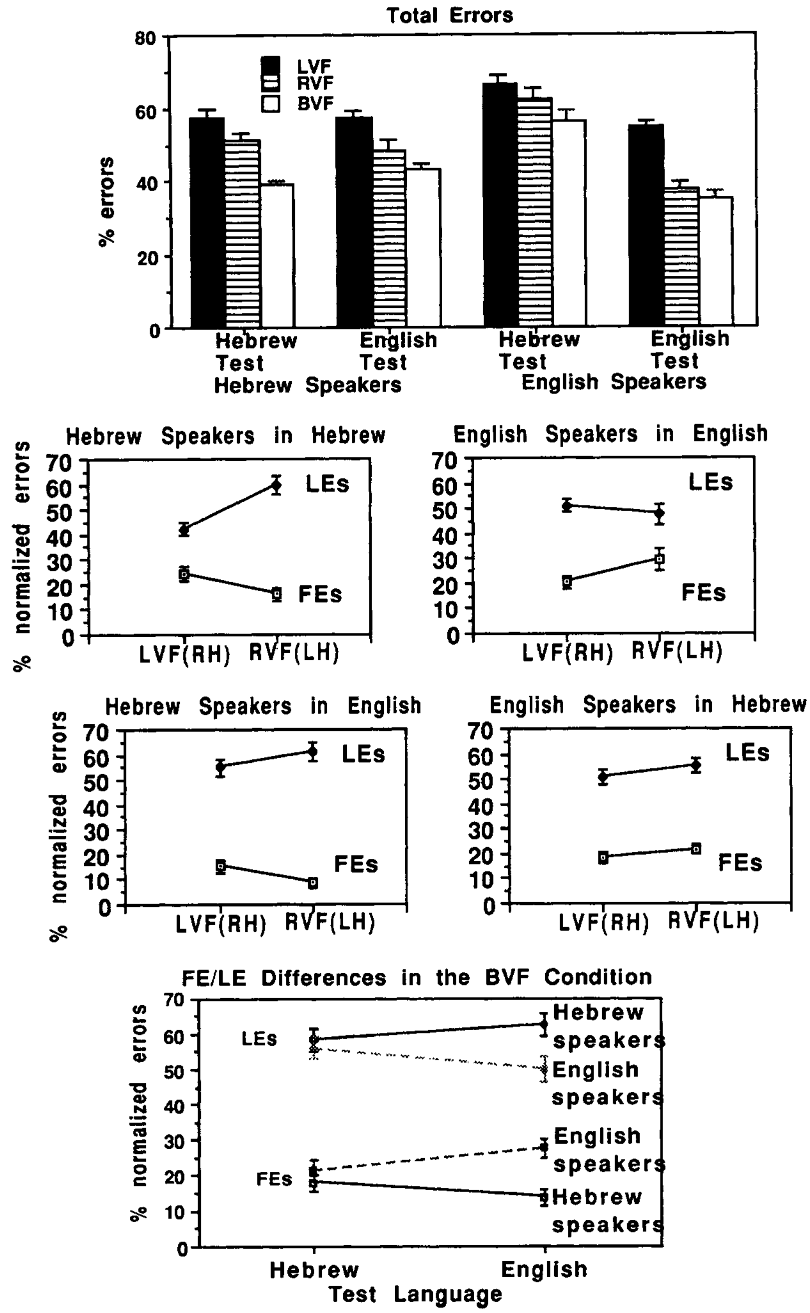

Figure 1. Top panel: Quantitative error patterns in the native language by test language experimental groups. Middle and bottom panels: Qualitative error patterns. LVF (RH) = left visual field (right hemisphere); RVF (LH) = right visual field (left hemisphere); BVF = bilateral presentation to both hemispheres simultaneously; LEs = percentages of errors on the last letter when the first letter was reported correctly out of the total errors in the visual field; FEs = percentages of errors on the first letter when the last letter was reported correctly out of the total errors in the visual field.

when the test language was the native language, $F(1, 38) = 8.00, p < .01$; that is, Hebrew speakers in Hebrew revealed a smaller RVFA than did English speakers in English. When the test language was the participants' second language, Hebrew and English speakers revealed a significant RVFA, $F(1, 38) = 6.10$, $p < .05$, of the same magnitude. The interaction of native language and visual field was not significant ($p > .3$).

Qualitative Error Scores

The normalized FEs and LEs were analyzed in three parts. First, FEs and LEs in the unilateral visual fields (LVF, RVF) from the four language conditions were analyzed to explore differences in hemispheric processing. Second, FEs and LEs in the bilateral condition were analyzed to explore differences between the language groups when both hemispheres saw the stimulus simultaneously. The third analysis compared the FE–LE difference in the BVF condition with those in the unilateral conditions; this measure of bias explored differences in hemispheric integration patterns between the language groups.

Unilateral patterns. The normalized FEs and LEs in each condition are presented in the four middle panels of Figure 1. These scores were analyzed with a four-way ANOVA using native language and test language as between-groups variables and visual field and error type (FEs vs. LEs) as within-group variables. The four-way interaction was not significant ($p > .8$). Three 3-way interactions were significant: Native Language × Test Language × Error Type, $F(1, 76) = 6.55$, $p < .05$, in which both groups of native speakers had a larger FE–LE difference when the test was in their second language than when it was in their native language; Native Language × Visual Field × Error Type, $F(1, 76) = 18.32$, $p < .0001$, indicating that the FE–LE difference was larger in the RVF for Hebrew speakers and larger in the LVF for English speakers; and Test Language × Visual Field × Error Type, $F(1, 76) = 5.22$, $p < .05$, in which the Visual Field × Error Type interaction was significant in the Hebrew test, $F(1, 38) = 12.66$, $p < .001$, but not in the English test ($p > .9$), across speakers of the two languages). The two-way interaction between native language and error type was significant, $F(1, 76) = 4.99$, $p < .05$, indicating that the FE–LE difference was larger overall for Hebrew speakers (38.90%) than for English speakers (28.82%). The two-way interaction between visual field and error type was significant, $F(1, 76) = 5.32$, $p < .05$, indicating that the difference between FEs and LEs was larger in the RVF (37.14%) than in the LVF (30.57%). The main effect of error type was significant, $F(1, 76) = 225.52$, $p < .0001$ (all participants made more LEs than FEs), as was the main effect of visual field, $F(1, 76) = 11.11$, $p < .005$ (overall, participants made fewer FEs and LEs, as a proportion of their total errors in each visual field, in the LVF [34.72%] than in the RVF [37.55%]).

Planned comparisons revealed that for the two groups of participants who performed the test in their native language (Hebrew speakers in Hebrew and English speakers in English), the interaction of language with visual field and error type was significant, $F(1, 38) = 16.12$, $p < .0005$. However, when speakers of the two languages performed the test in their second language (Hebrew speakers in English and English speakers in Hebrew), the effects of native language were weaker: The interaction of native language, visual field, and error type was not significant ($p = .09$). Further comparisons revealed that within each group of native speakers, the interaction of test language with visual field and error type was not significant ($ps > .11$ in both groups of speakers). That is, the language of the test did not affect the pattern of error types in the two visual fields. However, within each test language condition, the native language of the participants did interact with visual field and error type: for the Hebrew test, $F(1, 38) = 10.23$, $p < .005$, and for the English test, $F(1, 38) = 8.42$, $p < .01$. That is, in both the Hebrew and English versions of the test, the native language of the participants affected the pattern of error types in the two visual fields.

To more closely explore the relative effects of native language and test language on the patterns of error types in the visual fields, an asymmetry score was calculated for each participant by first computing a qualitative error score (LE − FE) and then using these scores to compute visual field asymmetries ($LVF_{LE-FE} - RVF_{LE-FE}$). These asymmetry scores were entered into a multiple regression model with native language, test language, and their interaction as predictors. Overall, 24% of the variance was explained by these variables. However, as suggested by the ANOVA results, 18.40% of the variance was explained by native language alone, whereas 5.24% was explained by test language alone, and less than 1% was explained by their interaction. This finding suggests that the native language and test language variables were independent and that the characteristics of the native language of the participants had a stronger effect on hemispheric strategies, as they were reflected in error types, than did the characteristics of the test language.

Bilateral patterns. The FE and LE scores from the bilateral condition were entered into a three-way ANOVA with native language and test language as between-groups variables and error type as a within-groups variable. The cell means are illustrated in the bottom panel of Figure 1. The three-way interaction approached significance, $F(1, 76) = 3.85$, $p = .0533$. This effect was due to the fact that both groups of native speakers showed a smaller FE–LE difference when the test was in their native language than when it was in their second language. The interaction between native language and error type was also significant, $F(1, 76) = 9.96$, $p < .005$. As in the unilateral conditions, the difference between FEs and LEs was larger for Hebrew speakers than for English speakers. The main effect of error type was significant, $F(1, 76) = 206.71$, $p < .0001$, with all participants making more LEs (56.68%) than FEs (20.09%). No other main effects or interactions were significant.

BIAS scores. The qualitative error scores were used to compute a bias score in the following manner. For each participant, the FE–LE difference (computed as LE − FE) in each visual field was entered into the following equation: $BIAS = |LVF - BVF| - |RVF - BVF|$. The first part of the equation represents the absolute value of the difference in error types between the LVF and the bilateral condition, whereas the second part represents the absolute value of the difference between the RVF and the bilateral condition. Thus, a negative score suggests that the pattern in the BVF is more similar to the one in the LVF (RH), whereas a positive value suggests that the pattern in the bilateral condition is more similar to the one in the RVF (LH). Using this measure, Hellige and his colleagues (e.g., Hellige & Cowin, 1996) have consistently found that the bilateral pattern is more similar to the one in the LVF than to the pattern in the RVF and have interpreted this finding as indicating that hemispheric cooperation involves the RH sequential strategy. These scores were analyzed using a 2 × 2 between-groups ANOVA with native language and test language as between-groups variables. The analysis revealed no significant effects, with the main effect of native language approaching significance, $F(1, 76) = 3.01$, $p = .087$. The mean scores were .046 ($SD = .242$) for Hebrew speakers in Hebrew, −.075 ($SD = .143$) for English speakers in English, .002 ($SD = .208$) for Hebrew speakers in English, and −.023 ($SD = .141$) for English speakers in Hebrew. Planned comparisons revealed that only the mean of the English speakers in English was significantly different from zero, $t(19) = -2.34$, $p < .05$. Like the results reported by Hellige and his colleagues (e.g., Hellige et al., 1994), these participants showed a qualitative error pattern more similar to the one in the LVF (RH) than to the score in the RVF (LH).

Analysis of other errors. The OE scores of the participants were analyzed with a three-way ANOVA using native language and test language as between-groups variables and visual field as a within-groups variable. The only significant effect was a main effect of visual field, $F(2, 152) = 11.32$, $p < .0001$, with all participants making more OEs in the LVF (30.55%) than in the RVF (24.90%) or the BVF (23.22%).

Independence of quantitative and qualitative measures. Previous studies using this paradigm (e.g., Eviatar, Hellige, & Zaidel, 1997) have shown that the asymmetry reflected in the quantitative (TEs) and qualitative (FEs and LEs) error scores is independent. To test this in this new sample, I computed a quantitative asymmetry score ($LVF_{TE} - RVF_{TE}$) and a qualitative asymmetry score ($LVF_{LE-FE} - RVF_{LE-FE}$) and looked for a correlation between them. As in previous reports, this was not significant for the sample as a whole nor for each native language by test language group. This result supports the hypothesis that the two measures index different aspects of hemispheric asymmetry.

Discussion

The results of Experiment 1 revealed several phenomena. First, both the quantitative and qualitative measures of the English speakers in English replicated the findings reported by Hellige and his colleagues (e.g., Hellige et al., 1994). These participants showed an RVFA in total errors, a larger difference between FEs and LEs in the LVF than in the RVF, and a bias index indicating that the qualitative pattern in the bilateral condition was more similar to the one in the LVF (RH) than in the RVF (LH). Second, the results of the Hebrew speakers in Hebrew revealed the same quantitative pattern, reflecting the fact that functional language lateralization patterns do not vary with language. However, the qualitative asymmetry revealed by these participants was in the opposite direction—the difference between FEs and LEs was significantly larger in the RVF than in the LVF. Third, participants performing the task in their second language (Hebrew speakers in English and English speakers in Hebrew) revealed patterns that were not significantly different from the patterns of those who performed the task in their native language. Finally, the average exposure durations needed by Hebrew speakers in their native language were more than twice as long as those needed by English speakers doing the task in English (76 ms vs. 36 ms, respectively) to achieve approximately the same error rate.

The second finding, that Hebrew and English speakers revealed the same quantitative asymmetry (an RVFA) but a different qualitative asymmetry in this task, together with the null correlations between these two measures, strengthens the hypothesis that these measures index different aspects of hemispheric asymmetry for this task. Specifically, the conclusions are that the LH superiority found for language tasks, irrespective of the characteristics of the languages, must reflect differences other than differential hemispheric use of parallel or sequential strategies.

The third finding, that qualitative patterns were similar in the native and nonnative test conditions and that native language explained 18% of the variance in FE–LE differences in asymmetry, suggests that reading strategies that are appropriate to a specific orthography are generalized by participants and also are used while processing a different orthography. However, this interpretation is limited by the fact that the Native Language × Visual Field × Error Type interaction was not significant between the Hebrew and English speakers who performed the test in their second language and by the interactions of test language with visual field and with error type in the overall analysis. That is, the characteristics of the language of the test do affect hemispheric strategies but seem to do so to a lesser extent than do the characteristics of the participants' native language.

The last finding, that to achieve approximately the same error rate, Hebrew demands longer exposures than does English, can be interpreted as reflecting several factors. First, the absence of diacritical marks in Hebrew allows more than one correct phonological form (e.g., the CVC גיח can be pronounced in at least three different ways), whereas in English, there is usually only one pronunciation resulting from grapheme–phoneme conversion rules (e.g., *POG*). Second, some of the possible phonological forms of the CVCs in Hebrew consisted of more than one syllable, whereas in English, all the nonwords consisted of one syllable. Third, Hebrew letters are less variable in shape than are English letters (most are variations on a square), such that identification of individual letters may be a harder task in Hebrew than in English. Studies investigating reading times and eye movements in the two languages have suggested that information is more densely packed in Hebrew orthography than in English orthography (Shimron, 1993; Shimron & Sivan, 1994). These factors converge with the qualitative error differences found above to suggest that the hemispheres of Hebrew and English readers may use different strategies to perform this lateralized task.

Experiment 2: Orthography and Sequential Processing

Experiment 2 was conducted to test the assumption that the FE–LE difference does indeed index sequential processing. The primary dependent variable was reaction time (RT). The stimuli were presented in the same format as that used in Experiment 1, but half of the stimuli contained the target letter *M* (or its equivalent מ in Hebrew). The task of the participants was target detection with manual responses. If the FE–LE difference indexes more sequential versus more parallel processes, then detection of the target letter in the last position should take longer than its detection in the first position. My prediction was that in English, there would be larger RT differences in the LVF between the conditions in which the target letter appeared in the first position and the conditions in which it appeared in the last position, with the opposite pattern seen in Hebrew. In addition, if, as suggested above, identification of Hebrew letters is a more difficult task than the identification of English letters, this should be reflected in overall longer RTs in Hebrew than in English.

Method

Participants

Three groups of participants took part in the experiment. One group of 17 native Hebrew speakers and two groups (each including 17 participants) of native English speakers were tested. All were chosen as described in Experiment 1. None had taken part in Experiment 1.

Design

The task was designed in the same way as in the task used in Experiment 1. The stimuli consisted of 37 unique vertically presented CVC trigrams. Of these, 18 included the letter *M* (in English) or מ ("mem" in Hebrew). The other letters in English were from the set *K, G, S, T,* and *B*, with the vowels being *A, O,* or *E*. In Hebrew, the other letters were from the set ל, ס, ח, ג, and ב, with the vowels being י, ו, or א The stimuli were presented in three blocks of 37 trials, with the 1st trial in each block never including the target. Participants completed one block of 37 trials as practice, using stimuli from a different set. Exposure duration was held constant across all trials. The native Hebrew speakers and one group of the native English speakers saw the stimuli for 80 ms, and the other group of native English speakers saw the stimuli for 40 ms. This was done to equate the groups on two separate variables: absolute exposure duration (Hebrew vs. English speakers when both groups saw the stimuli for the same amount of time) and relative exposure duration (80 ms was close to the mean exposure duration [76 ms] needed by native Hebrew speakers to reach a 50% error rate in Experiment 1, and 40 ms was close to the mean exposure duration [36 ms] needed by native English speakers to reach a 50% error rate). All other design variables were identical to those used in Experiment 1.

Procedure

All aspects of the procedure were the same as those used in Experiment 1 with two exceptions: The exposure duration was uniform throughout this experiment, and the participants were asked to press as quickly as they could a button marked "yes" if the target letter appeared and a button marked "no" if it did not appear. The response buttons were placed centrally and vertically to avoid stimulus–response compatibility.

Results

The median RTs to correct detections of the target in the first or the last position were analyzed in several ways. The first analysis compared the effects of language on this measure when both language groups were equated on the absolute exposure duration (80 ms) of the stimuli. The second analysis compared the same Hebrew speakers with a group of English speakers who saw the stimuli for only 40 ms, with the groups equated on relative exposure duration (as compared with the mean exposure duration needed by the participants in Experiment 1 to achieve a 50% error rate). The third analysis compared the two groups of English speakers to explore the effects of the different exposure durations on performance.

Unilateral Conditions

Both median RTs and misses were analyzed using a three-way ANOVA with language (Hebrew vs. English) as a between-groups variable and visual field and position (target in first position [FL] vs. target in last position [LL]) as within-subjects variables. The results of these analyses are shown in Table 2.

Groups equated on absolute exposure duration. These analyses compared the Hebrew speakers with the English speakers who saw the stimuli for the same amount of time (80 ms). The RT measure revealed that the three-way interaction between language, visual field, and position approached significance. As can be seen in the top row of Figure 2, the English speakers showed the same FL–LL difference in both visual fields (LL − FL = 63 ms in the LVF; LL − FL = 67 ms in the RVF). The Hebrew speakers showed a smaller FL–LL difference in the LVF (136 ms) than in the RVF (306 ms). The Position × Language interaction was significant, indicating that Hebrew speakers showed a much larger effect of position (LL − FL = 221 ms) than English speakers (LL − FL = 65 ms). The Visual Field × Language interaction was significant, indicating English speakers showed a nonsignificant left visual field advantage (LVFA; 16 ms, $p > .47$) and Hebrew speakers showed a significant RVFA (219 ms), $F(1, 16) = 4.79$, $p < .05$. The interaction of Visual Field × Position was significant, with the FL–LL difference larger in the RVF (187 ms) than in the LVF (100 ms). Last, each variable resulted in a significant main effect for language, with Hebrew speakers responding more slowly than English speakers (1,208 ms vs. 720 ms, respectively); position, with detection in the first position faster than detection in the last position (893 ms vs. 1,036 ms, respectively); and visual field, which approached significance, with responses in the RVF faster overall than responses in the LVF (913 ms vs. 1,015 ms, respectively).

Analyses of the misses revealed three significant effects: a two-way interaction between position and language, indicating that for English speakers the FL–LL difference was very

Table 2
Significant Effects in the Target Detection Task

Effect	Groups equated on absolute exposure duration	Groups equated on relative exposure duration
	Unilateral conditions	
Reaction time		
Language	$F(1, 32) = 24.19, p < .0001$	*ns*, $p > .3$
Visual field	$F(1, 32) = 3.95, p = .055$	$F(1, 32) = 4.24, p < .05$
Position	$F(1, 32) = 22.07, p < .0001$	$F(1,32) = 16.84, p < .0005$
Language × Visual Field	$F(1, 32) = 5.26, p < .05$	$F(1, 32) = 4.35, p < .05$
Language × Position	$F(1, 32) = 6.57, p < .05$	$F(1, 32) = 7.40, p < .05$
Visual Field × Position	$F(1, 32) = 4.19, p < .05$	*ns*, $p > .12$
Language × Visual Field × Position	$F(1, 32) = 3.81, p = .0598$	*ns*, $p > .2$
Misses		
Language	$F(1, 32) = 28.64, p < .0005$	*ns*, $p > .18$
Visual field	*ns*, $p > .3$	*ns*, $p > .4$
Position	$F(1, 32) = 16.85, p < .0005$	$F(1, 32) = 24.72, p < .0001$
Language × Visual Field	*ns*, $p > .3$	*ns*, $p > .4$
Language × Position	$F(1, 32) = 11.83, p < .005$	*ns*, $p > .9$
Visual Field × Position	*ns*, $p > .2$	*ns*, $p > .7$
Language × Visual Field × Position	*ns*, $p > .7$	*ns*, $p > .3$
	Bilateral conditions	
Reaction time		
Language	$F(1, 32) = 21.40, p < .0005$	*ns*, $p > .7$
Position	$F(1, 32) = 16.66, p < .0005$	$F(1, 32) = 10.75, p < .005$
Language × Position	$F(1, 32) = 11.72, p < .005$	*ns*, $p > .2$
Misses		
Language	$F(1, 32) = 20.12, p < .0001$	*ns*, $p > .9$
Position	$F(1, 32) = 8.73, p < .0005$	$F(1, 32) = 10.75, p < .005$
Language × Position	$F(1, 32) = 8.73, p < .0005$	*ns*, $p > .6$

small (0.98, $p > .4$) and for Hebrew speakers it was large (11.11), $F(1, 16) = 18.13$, $p < .001$; the main effect of language, with English speakers making fewer misses (3.43) than Hebrew speakers (14.38) overall; and the main effect of position, with fewer misses made on targets in the first position (5.88) than in the last position (11.93).

Groups equated on relative exposure duration. These analyses compared the Hebrew speakers with the English speakers who saw the stimuli for 40 ms. The RT measure revealed that the three-way interaction between language, visual field, and position was not significant. The Position × Language interaction was significant, with the FL–LL difference larger and significant in the Hebrew speakers (221 ms), $F(1, 16) = 15.83$, $p < .005$, and smaller and not significant in the English speakers (54 ms, $p > .19$). The main effect of visual field was significant, with detections in the RVF (1,083 ms) faster than those in the LVF (1,192 ms), as was the main effect of position, with letters in the first position detected faster (1,071 ms) than those in the last position (1,204 ms). The main effect of language was not significant ($p > .3$). Analysis of the misses revealed only a main effect of position, with letters in the first position missed less (6.86) than those in the last position (17.81).

Bilateral Condition

The median RTs from the bilateral condition were analyzed with a two-way ANOVA using target position as a within-subjects variable and language as a between-subjects variable. The significant effects of both comparisons are shown in Table 2. The cell means are illustrated in the two bottom panels of Figure 2. As can be seen in Table 2 and Figure 2, comparisons of the groups equated on absolute exposure duration resulted in significant effects for language (English speakers = 716 ms, Hebrew speakers = 1,139 ms) and position (FL = 852 ms, LL = 1,003 ms) and a significant interaction between them for both RTs and misses, as position affected responses of the Hebrew speakers and not of the English speakers. Comparisons of the groups equated on relative exposure duration resulted only in an effect of position in misses, with both language groups making more misses on letters in the last position than in the first position. Again, the main effect of language was not significant.

Exposure Duration and Sequential Processing

This analysis compared the two groups of English speakers. Exposure duration affected overall RTs, with the participants who saw the stimuli for 80 ms responding faster than those who saw the stimuli for 40 ms in both the unilateral (720 ms vs. 1,066 ms, respectively) and the bilateral conditions (716 ms vs. 1,095 ms, respectively). The effect of shorter exposure duration in misses was on the FL–LL difference, where the interaction of exposure duration and target position was significant, $F(1, 32) = 6.65$, $p < .05$. Interestingly, there was no difference between the groups in misses in the first position ($p > .2$) and a significant difference in misses in the last position, $F(1, 32) = 8.02$, $p < .01$. That is, shorter exposure duration resulted in more LL misses but did not affect FL misses.

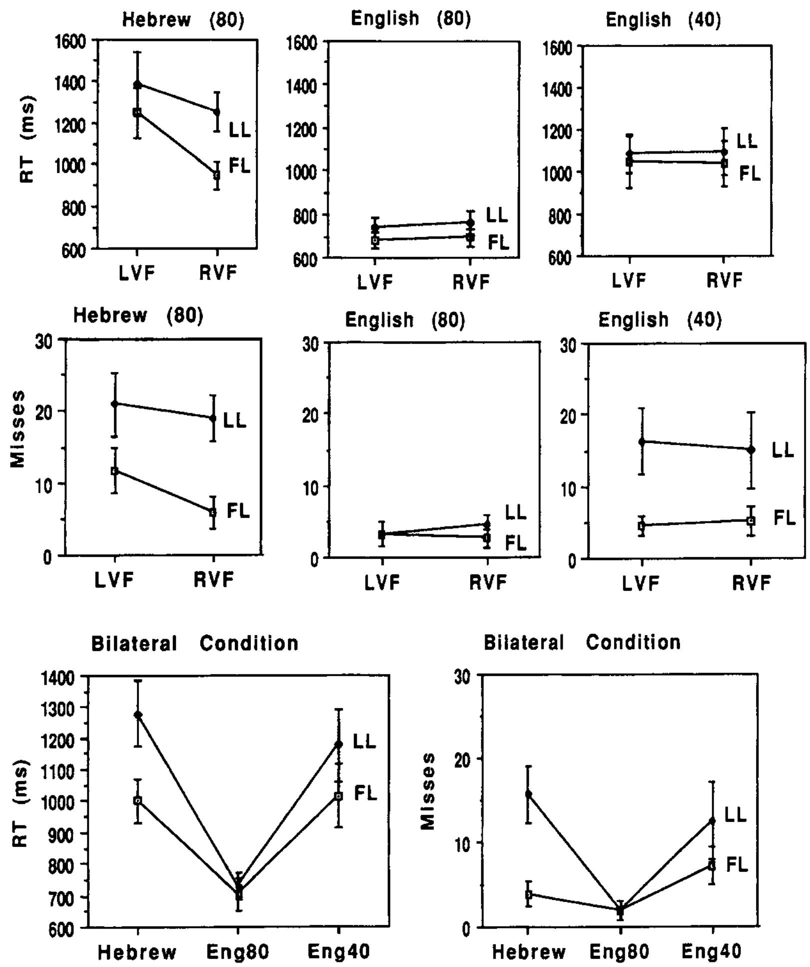

Figure 2. Top row: Mean median response times to first letter (FL) targets and last letter (LL) targets in the unilateral visual presentation conditions (LVF = left visual field; RVF = right visual field) for the groups of Hebrew and English speakers who saw the stimuli for 80 ms (Hebrew 80 and English 80) and for the group of English speakers who saw the stimuli for 40 ms (English 40). Middle row: Mean misses to FL and LL targets in the unilateral visual presentation conditions for the groups of Hebrew and English speakers who saw the stimuli for 80 ms (Hebrew 80 and English 80) and for the group of English speakers who saw the stimuli for 40 ms (English 40). Bottom row: Mean median response times (left panel) and misses (right panel) of the three groups in the bilateral presentation condition. Eng = English.

Bias

A bias measure was calculated to explore the sequentiality effect in the unilateral conditions versus the bilateral condition. This was done by computing the FL–LL difference in each visual presentation condition and computing

$$\text{Bias} = |\text{LVF}_{\text{LL-FL}} - \text{BVF}_{\text{LL-FL}}| - |\text{RVF}_{\text{LL-FL}} - \text{BVF}_{\text{LL-FL}}|.$$

If this value is a negative number, it reflects that sequentiality (longer RTs to detect letters in the last position than in the first position) is of similar magnitude in the LVF and the bilateral condition, whereas a positive number indicates greater similarity between the RVF and the bilateral condition. The values of the bias measure were 145 ms for Hebrew speakers, 11 ms for English speakers with an 80-ms exposure duration, and −51 ms for English speakers with a 40-ms exposure duration. Comparison of the bias scores revealed that the two English-speaking groups did not differ from each other ($p > .4$), although both differed from the Hebrew speakers: $t(32) = -2.185$, $p < .05$, for groups equated on absolute value; $t(32) = -2.143$, $p < .05$, for groups equated on relative value. Only the bias value of the Hebrew speakers was significantly different from zero, $t(16) = 2.59$, $p < .05$.

Discussion

The goal of Experiment 2 was to see if RTs to letters in the first and third positions would result in the same pattern of asymmetry as errors. The results showed that this was so for Hebrew speakers because they showed a larger difference between letters in the first position and in the last position in the RVF than in the LVF, corresponding to the asymmetry in FE–LE differences in Experiment 1. For English speakers, neither group showed a Visual Field × Position interaction or even an RVFA for RTs and misses. Given that the English speakers in Experiment 1 did show an RVFA in errors, this suggests that the processes underlying the letter detection task here were different from those used by the participants in Experiment 1. The effects of exposure duration suggest that English speakers did use a sequential process to identify the letters of the CVC and that 80 ms was enough time for them to process all three positions whereas 40 ms was not. This is supported by the finding that there was no effect of exposure duration for letters in the first position whereas shorter durations resulted in significantly more misses in the last position. Thus, it can be concluded that the FE–LE difference overall does reflect sequential processes for both language groups; however, there is evidence for an asymmetry in these processes only for the Hebrew speakers. In addition, the effects of language on RT support the hypothesis that Hebrew letters are more difficult to identify than English letters.

The possibility that the large differences in exposure duration in Experiment 1 affected the patterns of responses was explored by reanalyzing the data from Experiment 1 and computing an analysis of covariance on the qualitative error asymmetry, parceling out exposure duration. Recall that the qualitative error asymmetries are the difference between FE–LE differences between the two visual fields, with a negative score indicating larger FE–LE differences in the RVF than in the LVF and a positive score indicating the opposite pattern. This analysis revealed that the effect of native language was still significant, $F(1, 75) = 16.80, p < .0001$, whereas both the effect of test language and the interaction between test language and native language were not significant ($p > .2$). Therefore, it can be concluded that the opposing patterns of qualitative asymmetries in the two language groups in Experiment 1 were not due to confounding effects of different exposure durations.

Experiment 3: Number Trigrams

Experiment 3 was done to test if the opposing qualitative error patterns in the two language groups would occur for number trigrams. This question is interesting because the use of number trigrams actually overcomes all the major differences between the languages (stimulus discriminability, reading direction, orthography–phonology relations, and morphological structure). In Hebrew, numbers are read as they are in English, from left to right. The morphology of number names is also similar, in that 472 is named "four hundred and seventy-two" in English and "four-hundred-seventy and two" in Hebrew.

Method

Participants

Twenty native Hebrew speakers and 20 native English speakers were selected as were the participants for the previous experiments.

Materials and Procedure

The experiment was designed exactly like Experiment 1 except that the trigrams were constructed from the set of numbers 1–9. No trigrams included doubled or tripled numbers (e.g., 233 or 444). The task of the participants was to name the number (e.g., "four hundred seventy-two") and then to name its constituents ("four, seven, two").

Results

Exposure Duration

The titration of exposure duration to achieve a 50% error rate was effective, with English speakers making 48.19% errors and Hebrew speakers making 48.24% errors overall. The mean exposure durations were analyzed with language as a between-subjects variable. The analysis revealed a main effect of language, $t(38) = 4.125, p < .005$, with English speakers requiring a shorter exposure duration (66 ms) than Hebrew speakers (108 ms). The interaction of the variables was not significant ($p > .5$).

Total Errors

The percentages of errors in each visual field for the two language groups are illustrated in the top panel of Figure 3. The analysis revealed only a main effect of visual field, $F(2, 76) = 27.29, p < .0005$. No other effects were significant. Planned comparisons showed that the RVFA was significant for both language groups: for English speakers, $F(1, 19) = 5.51, p < .05$, and for Hebrew speakers, $F(1, 19) = 9.10, p < .01$.

Qualitative Errors

The normalized FEs and LEs were analyzed as were those for Experiment 1. Analysis of the unilateral conditions revealed two significant effects: a main effect of error type, $F(1, 38) = 108.87, p < .0001$ (FEs = 13.01% and LEs = 54.98%), and a three-way interaction between visual field, error type, and language, $F(1, 38) = 12.60, p < .005$. This interaction is illustrated in the middle panels of Figure 3. Planned comparisons showed that for both language groups, the main effect of error type was significant: for English speakers, $F(1, 19) = 114.65, p < .0001$, and for Hebrew speakers, $F(1, 19) = 29.92, p < .0001$, as was the interaction between visual field and error type: for English speakers, $F(1, 19) = 7.23, p < .05$, and for Hebrew speakers, $F(1, 19) = 5.58, p < .05$. As can be seen in Figure 3, this interaction was in the opposite direction in the two language groups. Analysis of the BVF condition revealed only a main effect of error type, $F(1, 38) = 196.72, p <$

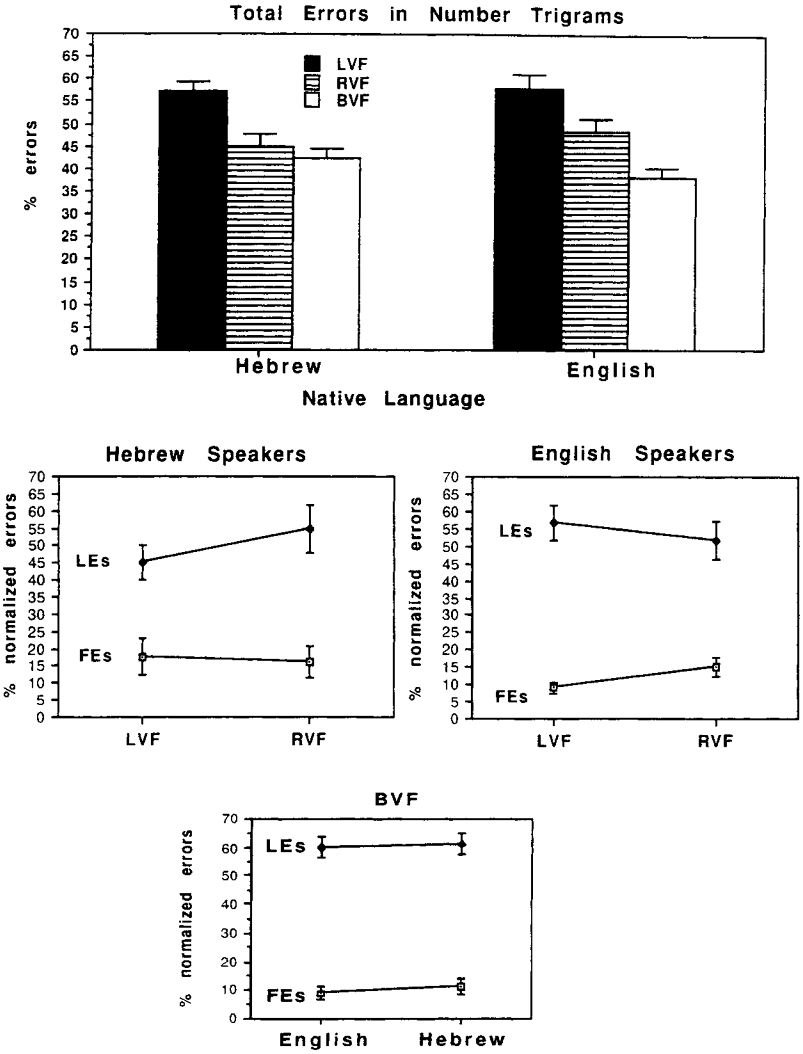

Figure 3. Top panel: Quantitative errors for number trigrams by Hebrew and English speakers. Middle panels: Qualitative error patterns for number trigrams by Hebrew and English speakers. Bottom panel: Qualitative errors for number trigrams in the BVF condition. LVF = left visual field; RVF = right visual field; BVF = bilateral presentation to both hemispheres simultaneously; LEs = percentages of errors on the last letter when the first letter was reported correctly out of the total errors in the visual field; FEs = percentages of errors on the first letter when the last letter was reported correctly out of the total errors in the visual field.

.0001, and no main effect of language ($p > .4$) nor an interaction between the variables ($p > .9$). These scores are presented in the bottom panel of Figure 3. Analyses of bias scores revealed a main effect of language, $t(38) = 3.52, p < .005$, with English speakers revealing a slightly negative score (−.05) that was not significantly different from zero ($p > .1$) and Hebrew speakers showing a significant positive score (.11), $t(19) = 3.35, p < .005$. Analysis of OEs revealed only a trend toward a main effect of visual field, $F(2, 76) = 3.07, p = .052$, and no main effect of language ($p > .5$) nor an interaction between visual field and language ($p > .3$).

Qualitative ($LVF_{LE-FE} - RVF_{LE-FE}$) and quantitative ($LVF_{TE} - RVF_{TE}$) asymmetry scores were computed as they were for Experiment 1. Correlational analyses revealed that these asymmetries were not related in the sample overall ($p > .3$) nor in each language group separately. The analyses comparing the two groups of English speakers in Experiment 2 suggested that exposure duration of the stimuli can have an effect on the FE–LE differences. Therefore, I computed analyses of covariance on the qualitative asymmetry scores using mean exposure duration as the covariate. This analysis revealed that parceling out the effects of exposure duration reduced the effect of language, $F(1, 36) =$

3.29, $p = .07$. However, the estimated mean qualitative asymmetry was still in the opposite direction in the two language groups (a positive 6.99% difference between the visual fields in English, reflecting the larger FE–LE differences in the LVF than in the RVF, and a negative 10.73% difference for Hebrew speakers, reflecting the opposite pattern).

Discussion

Experiment 3 was done to explore the asymmetry patterns for FEs and LEs in the two language groups for number trigrams. These stimuli were identical for the English- and Hebrew-speaking participants, as were the conventions for reading and naming them. Interestingly, again the quantitative measure resulted in an RVFA for both groups, but the qualitative measure showed the opposite asymmetry patterns, even when the effects of different exposure durations were parceled out. These results are similar to the results of Experiment 1. The results also revealed the same effect of native language on exposure duration, with Hebrew speakers requiring exposure durations longer by 44 ms to achieve the same error score as English speakers (the difference between the native groups in Experiment 1 was 40 ms). A comparison of the two native language conditions from Experiment 1 with those of Experiment 3 was done, using stimuli (numbers vs. letters) as an additional between-groups variable. As suggested by the results of Experiment 3, the three-way interaction between visual field, error type, and language was significant, $F(2, 154) = 20.06, p < .0001$, whereas the four-way interaction between visual field, error type, language, and stimuli was not significant ($p > .16$). The conclusion from these findings is that the participants in Experiment 3 used the same processes to identify the number trigrams that the participants in Experiment 1 used to identify the letter trigrams, such that the effects of the differences in the native languages can be seen with these stimuli as well.

These results converge with those of Experiment 1 and with other findings that have shown effects of reading habits on performance asymmetries in other tasks (Eviatar, 1997; Morikawa & McBeath, 1992; Vaid & Singh, 1989). The conclusion from these studies is that habits of attention deployment and specific processes necessary for normal reading in different languages are reflected in different patterns of measures of hemispheric functions, even when the stimuli are identical (as in the comparisons of both Hebrew and English speakers doing the task in English in Experiment 1 or with numbers in Experiment 3) and even when the stimuli are not related to language at all, as in the chimeric faces task (Eviatar, 1997; Vaid & Singh, 1989). These findings suggest that caution must be used when models of hemispheric function are based on speakers of only one language or on languages with similar characteristics and highlight the theoretical importance of cross-language and cross-cultural studies for models of the functioning of the modal brain.

Experiment 4: Horizontal Presentations

The results of Experiments 1 and 3 suggest that Hebrew and English speakers use different hemispheric strategies to perform these trigram identification tasks. The results of Experiment 2 suggest that Hebrew letters are harder to discriminate than English letters, although the results of Experiment 3 and the analysis of covariance on the results of Experiment 1 showed that the effects of exposure duration did not completely eliminate the effects of language. As mentioned previously, there are several reasons to believe that orthographic and morphological differences between the languages result in somewhat different strategies in reading. Several recent psycholinguistic studies (e.g., Berent & Shimron, 1997; Feldman, Frost, & Pnini, 1995) have shown that Hebrew readers reveal sensitivity to the abstract root (recall that the root in Hebrew is not a word) and have suggested that the root is psychologically real, in the sense that it is a separate constituent in the representation of Hebrew words. It is not clear how this affects the identification of nonwords. There are two possible routes to the pronunciation of the nonsense CVC stimuli: a nonlexical grapheme–phoneme conversion route and a lexical or neighborhood route, in which the nonwords are compared with real words that they resemble and the phonological form of the real word is transferred to the nonword. As mentioned previously, in its unvoweled form, Hebrew orthography omits almost all vowel information. This suggests that the grapheme–phoneme route to pronunciation even of nonwords may not be the strategy of choice in Hebrew and that lexical access may be necessary for this task in Hebrew, but not in English, in which the CVCs can specify a unique phonological form.

Koriat and Norman (1985) showed that vertically presented (unvoweled) Hebrew words are mentally rotated to the canonical horizontal position before lexical access. They suggested that this happens because the root must be extracted from the letter string before lexical access can occur, that transgraphemic information is needed to access the lexicon, and that this information is extracted from the horizontal form. If the nonwords were named by means of real words that they resemble after lexical access, the participants may have needed to mentally rotate the vertical nonsense CVCs in Hebrew in a clockwise direction to be able to read them from right to left, as Hebrew is read. In English, if rotation took place, it was in the opposite direction to read from left to right. Burton, Wagner, Lim, and Levy (1992) suggested that there are hemispheric differences in preferred rotation direction, such that the RH is better at clockwise and the LH is better at counterclockwise rotation. Thus, one possible explanation for the large LE rate in the RVF in the Hebrew condition may be that the LH was rotating the letters in the nonpreferred direction and the last letter, which had to be mentally moved the largest distance, was lost more often than in the LVF (RH) condition. In English, it would be the RH that was rotating the words in the nonpreferred direction. However, Hellige and Cowin (1996) reported evidence contradicting this rotation interpretation of visual field differences, at least for English. They presented horizontal lateralized CVC trigrams to native English speakers and found that the FE–LE asymmetry was still present and significant and concluded that it resulted from different hemispheric strategies of CVC identification that were independent of letter arrangement.

In Experiment 4, native Hebrew speakers and native English speakers performed the task in their respective native languages with the stimuli aligned horizontally. If the previous language differences resulted from rotation differences due to reading direction, this manipulation should eliminate the language effect. However, if these differences result from different nonword reading strategies in the two languages, the language effect should persist.

Method

Participants

Forty participants completed the experiment. Twenty native Hebrew speakers and 20 native English speakers were recruited as were the participants for the previous experiments.[3]

Materials

The stimuli were identical to the Hebrew and English vertical presentation versions described in Experiment 1. The only difference was that the stimuli were presented horizontally, with the middle letter 2° of visual angle from fixation.

Procedure

The procedure was the same as that used in the native language conditions of Experiment 1.

Results

Exposure Duration

Titration of exposure duration to achieve an approximately 50% error rate was successful; the overall error rate in Hebrew was 49.21% and in English 43.66%. Analysis of the exposure durations revealed that as in Experiments 1 and 3, Hebrew speakers required longer exposure durations than English speakers, $F(1, 38) = 17.07$, $p < .0005$ (Hebrew speakers = 68 ms and English speakers = 40 ms).

Total Errors

The percentages of errors in each visual field for the two groups were analyzed with a two-way ANOVA using language (Hebrew or English) as a between-groups variable and visual field (LVF, RVF, or BVF) as a within-groups variable. These data are illustrated in the top panel of Figure 4. There was a main effect of language, $F(1, 38) = 10.93$, $p < .005$, with Hebrew speakers making more errors than English speakers, and a main effect of visual field, $F(2, 76) = 47.67$, $p < .0001$. As can be seen in Figure 4, both groups of participants revealed an RVFA and a bilateral advantage. There was no interaction between language and visual field ($p > .1$).

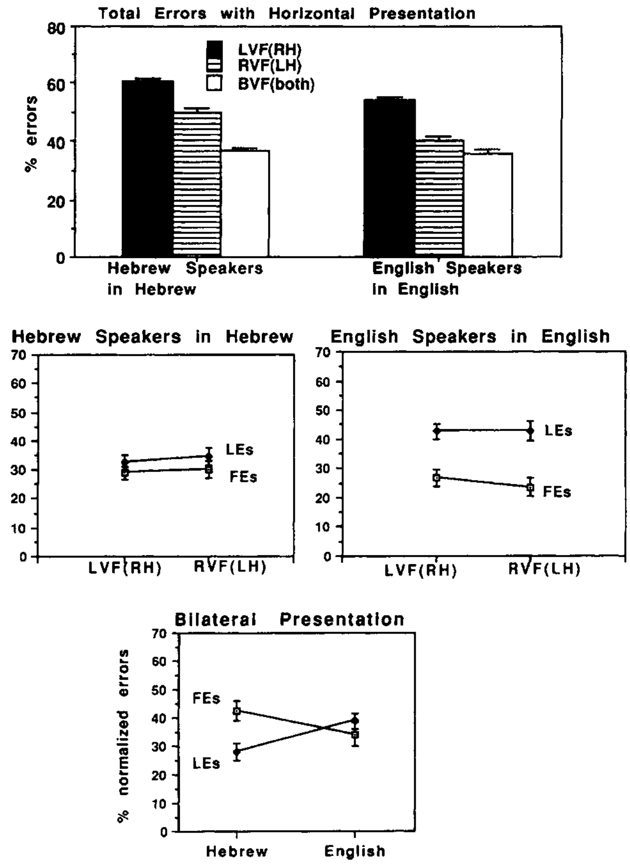

Figure 4. Quantitative and qualitative error patterns from the horizontal presentation condition. Top panel: Visual field differences in total errors (quantitative asymmetries). Middle panels: Qualitative error patterns in the unilateral visual fields. Bottom panel: Qualitative errors in the bilateral presentation. LVF (RH) = left visual field (right hemisphere); RVF (LH) = right visual field (left hemisphere); BVF = bilateral presentation to both hemispheres simultaneously; LEs = percentages of errors on the last letter when the first letter was reported correctly out of the total errors in the visual field; FEs = percentages of errors on the first letter when the last letter was reported correctly out of the total errors in the visual field.

Qualitative Error Patterns

Unilateral patterns. The normalized FEs and LEs from the unilateral conditions were analyzed with a three-way ANOVA using native language as a between-groups variable and visual field and error type as within-groups variables. Two effects were significant: the main effect of error type, $F(1, 38) = 22.74$, $p < .0001$, and the interaction of native language and error type, $F(1, 38) = 9.10$, $p < .005$. Here, the FE–LE difference was larger for English speakers (17.45%) than for Hebrew speakers (3.39%). No other effects or interactions were significant. These patterns are illustrated in the middle panels of Figure 4.

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[3] Sections of the data from these samples were reported in Eviatar (1996).

Bilateral patterns. The normalized FEs and LEs from the two language groups in the bilateral condition were analyzed with language as a between-groups variable and error type as a within-groups variable. These are shown in the bottom panel of Figure 4. Only the interaction between the variables was significant, $F(1, 38) = 5.20, p < .05$. Here, the FE–LE difference was in the opposite direction in the two languages. Planned comparisons revealed that the FE–LE difference for English speakers was not significant ($p > .5$), whereas for Hebrew speakers, the FE–LE difference was flipped (they made more FEs than LEs), and this difference was significant, $F(1, 19) = 6.01, p < .05$. Analysis of the bias measure revealed that both groups evinced bias scores that were not significantly different from zero (English speakers = $-.077$, $p > .14$; Hebrew speakers = $-.049, p > .4$) and did not differ from each other ($p > .7$).

Other errors. Analysis of the OEs with language as a between-groups variable and visual field as a within-groups variable revealed only a main effect of visual field, $F(2, 76) = 3.37, p < .05$, with both language groups making less errors in the bilateral condition than in the unilateral conditions (LVF = 34.53%, RVF = 34.72%, and BVF = 28.24%).

Intermeasure correlations. Correlations were computed for the qualitative and quantitative asymmetry measures as they were in Experiments 1 and 3. These were not significant for the sample as a whole nor for each language group separately ($p > .5$ in all cases).

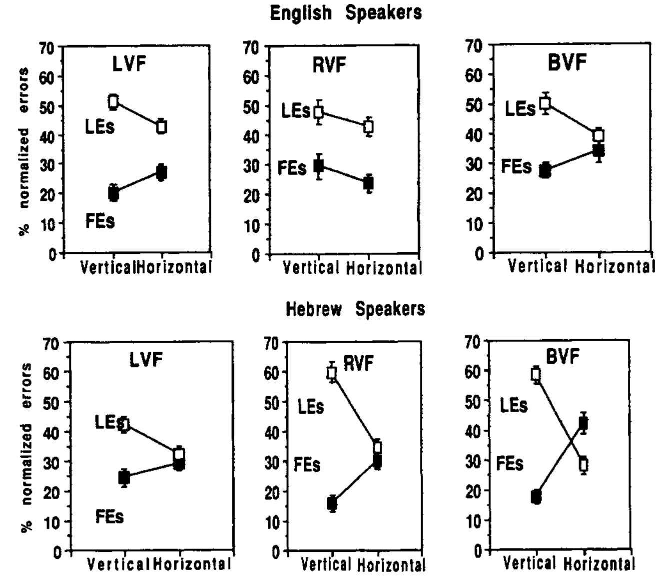

Figure 5. The effects of orientation of qualitative error patterns in each visual field for English and Hebrew speakers. LVF = left visual field; RVF = right visual field; BVF = bilateral presentation to both hemispheres simultaneously; LEs = percentages of errors on the last letter when the first letter was reported correctly out of the total errors in the visual field; FEs = percentages of errors on the first letter when the last letter was reported correctly out of the total errors in the visual field.

Comparison With the Vertical Conditions

The effects of orientation (vertical vs. horizontal stimulus presentation) on the normalized error scores were explored by comparing the native language conditions in Experiment 1 (Hebrew speakers doing the test in Hebrew and English speakers doing the test in English) with the present results. The effects of orientation on both the unilateral and bilateral conditions are illustrated in Figure 5.

Unilateral conditions. The normalized FE and LE scores from the unilateral conditions were analyzed using a four-way ANOVA with language and orientation as between-groups variables and visual field and error type as within-groups variables. As suggested by Figure 5, the four-way interaction between these variables was significant, $F(1, 77) = 8.49, p < .005$.[4] To better understand this interaction, the effects of language, orientation, and error type were explored separately in each visual field. This analysis revealed that for English speakers, orientation affected qualitative errors in the LVF, $F(1, 38) = 5.53, p < .05$, but not in the RVF ($p > .9$), whereas for Hebrew speakers, orientation affected qualitative error scores in both visual fields: for the LVF, $F(1, 39) = 5.00$, $p < .05$, and for the RVF, $F(1, 39) = 25.40, p < .001$.

Bilateral conditions. The normalized FE and LE scores from the bilateral conditions in the vertical and horizontal experiments were analyzed with a three-way ANOVA using language and orientation as between-groups variables and error type as a within-groups variable. This analysis revealed a significant effect of error type, $F(1, 77) = 25.03$, $p < .0001$, and a significant three-way interaction, which is illustrated in the rightmost panels of Figure 5. Planned comparisons in each orientation revealed that in both vertical and horizontal conditions, the interaction of language with error type was significant: for the vertical condition, $F(1, 39) = 6.69$, $p < .05$, and for the horizontal condition, $F(1, 38) = 5.20, p < .05$. In both orientations, the main effect of language was not significant, and the main effect of error type was highly significant in the vertical condition, $F(1, 39) = 82.39$, $p < .0001$, but not in the horizontal condition, $p > .25$.

Other errors. The OE scores of the participants from the two orientation conditions and the two language conditions were analyzed with a three-way ANOVA using language and orientation as between-groups variables and visual field as a within-groups variable. Only the main effects of orientation, $F(1, 77) = 12.31$, $p < .001$, and visual field, $F(2, 154) = 6.97$, $p < .005$, were significant, with participants making more OEs in the horizontal condition (32.49%) than in the vertical condition (25.92%) and fewer OEs in the bilateral condition (25.65%) than in the unilateral conditions (LVF = 32.71% and RVF = 29.14%).

Discussion

Experiment 4 was conducted to see if the opposing patterns of FE–LE asymmetry between the language groups

[4] This interaction is reported in Eviatar (1996).

occurred when the stimuli were presented horizontally. The analysis of these data revealed that they did not. The effect of horizontal presentation in both language groups was to lessen the FE–LE difference (in the English-speaking group and to eliminate it in the Hebrew-speaking group). In both the unilateral and bilateral conditions, the only effect of language was a smaller (and even negative, in the bilateral condition) FE–LE difference for Hebrew speakers than for English speakers. That is, if making more LEs than FEs is an indication of sequential processing, Hebrew speakers do not process horizontal stimuli sequentially, whereas English speakers do so.

As can be seen in Figure 4, the horizontal presentation condition with English speakers did not replicate the results reported by Hellige and Cowin (1996), which is the only other study that has used horizontal presentations in this paradigm. That is, the participants in the present experiment did not show an asymmetry in FE–LE differences when the stimuli were presented horizontally. It is probable that this different pattern resulted from methodological differences between the studies (Sergent & Hellige, 1986). The experiments reported here used a larger stimulus size than did Hellige and Cowin and a computerized rather than a slide presentation. These factors probably contributed to the shorter exposure durations needed by English speakers in this study (122–123 ms reported by Hellige and Cowin [1996] vs. 40 ms in Experiment 4). The results of Experiment 2 suggest that exposure duration affects the FE–LE difference. Therefore, I computed an analysis of covariance, comparing the qualitative asymmetries ($LVF_{LE-FE} - RVF_{LE-FE}$) from Hellige and Cowin's study and from the present Experiment 4, parceling out exposure duration. This analysis revealed that the asymmetries in the two studies did not differ significantly ($p > .09$).

The results of horizontal presentation in the unilateral conditions support the hypothesis that in Hebrew all of the letters in both visual fields are processed in parallel. This finding may be explained in the following way: Reading in Semitic languages requires identification of the root morpheme prior to lexical access (Farid & Grainger, 1996; Koriat & Norman, 1985). Given that Hebrew has nonconcatenative morphology and the letters of the root may be dispersed across positions in the word, it may not be possible to read Hebrew in a serial letter-by-letter manner (see Birnboim, 1995, for the implications of this feature of Hebrew for the symptoms of acquired surface dyslexia). Therefore, it is reasonable to assume that the normal strategy of skilled readers in Hebrew is a parallel one, with the quantitative asymmetry reported in previous studies (e.g., Faust et al., 1993) and in the total error measures in the experiments reported here reflecting differential hemispheric abilities for language that are not related to parallel or sequential processing strategies. In Experiment 4, the task of the participants was to pronounce the nonsense word and then to spell it. If unvoweled Hebrew nonwords require lexical access in order to use a neighborhood route for pronunciation, the Hebrew speakers used this parallel strategy to extract the transgraphemic information necessary for lexical access, resulting in no FE–LE differences in either visual field. English, in contrast, has a concatenative morphology, which allows sequential processing of letters, and this is reflected in the FE–LE difference in both visual fields in these data and in the data reported by Hellige and Cowin (1996).

The data also may support the hypothesis that in the vertical condition, Hebrew speakers were mentally rotating the stimuli in a clockwise direction, so the larger LE rate in the RVF is a reflection of it having to be moved the largest distance in the nonpreferred rotation direction of the LH. The data are equivocal as to whether the English speakers rotated the vertical stimuli. To read from left to right, the stimuli had to be rotated in a counterclockwise direction, which is preferred by the LH. English speakers made more LEs in the vertical condition than in the horizontal condition only in the LVF, where the RH was presumably rotating the stimuli in the nonpreferred direction. Thus, it may be that the opposing patterns of FE–LE differences in the unilateral visual fields between Hebrew and English speakers in Experiment 1 resulted from the opposing reading scanning directions in the two languages, which demand mental rotation of vertical stimuli in opposite directions.

Comparison of the vertical and horizontal conditions suggests that the hemispheres of Hebrew and English speakers react differently to changes in the orientation of the stimuli. For English speakers, the orientation of the stimuli did not affect the qualitative pattern of errors in the RVF (LH) but did affect these patterns in the LVF (RH). For Hebrew speakers, orientation affected the qualitative error pattern in both visual fields (see Figure 5). The pattern shown by the English speakers converges with the findings and conclusions of Marsolek and his colleagues (Marsolek, Kosslyn, & Squire, 1992; Marsolek, Schacter, & Nicholas, 1996), who suggested that the RH is more sensitive than the LH to the form-specific information of verbal stimuli. Using a variety of tasks with word stimuli, they found that manipulation of the script in which the stimuli were presented affected LVF but not RVF responses. They suggested that there are two visual-form subsystems: one that encodes specific visual form, underlies recognition of specific instances, and is differentially active in the RH and one that encodes abstract visual form, underlies category recognition, and is differentially active in the LH. The finding regarding the performance of the English speakers presented here supports this hypothesis, but that this was not true for Hebrew speakers is important because it joins other studies that have used non-English speakers and have questioned the generality of models of hemispheric functioning that are mainly based on participants from Western cultures who mainly read Latin scripts (Eviatar, 1997; Vaid & Singh, 1989).

General Discussion

The results of the four experiments support the hypothesis that the opposing qualitative error scores in the two languages result from reading strategies that are constrained by the orthographic and morphological characteristics of the languages. In English, the results of both vertical and horizontal presentations support the hypothesis that nonwords are processed differently in the two hemispheres, with the RH performing serial letter-by-letter identification, whereas the LH, although still showing signs of sequential processing, is able to deploy attention more evenly across the first and last letters of the stimulus. In Hebrew, vertical presentation results in serial processing in both hemispheres, because the noncanonical presentation disallows the use of the normal parallel strategy that is used by both hemispheres in the canonical (horizontal) presentation condition. I have suggested that this is due to the structural characteristics of the languages. Reading Hebrew requires attention to be deployed to all the constituents of the stimulus in parallel to identify the root letters, whereas reading English does allow sequential processing of the letters in both hemispheres, which resulted in the FE–LE differences even in the horizontal condition.

Correlational analyses of the qualitative and quantitative asymmetries in Experiments 1, 3, and 4 revealed that these were not related. This also was found by Eviatar et al. (1997) and strongly suggests that the quantitative and qualitative asymmetries yielded by this paradigm index different aspects of hemispheric asymmetries. As mentioned in the introduction, many studies have shown LH specialization for language tasks, irrespective of the characteristics of the language. This specialization is what is indicated by the quantitative asymmetries in the experiments reported here and does not seem to depend on whether a parallel or a sequential process is used to complete the task. The finding of different qualitative patterns that are dependent on the characteristics of the language (English, Hebrew, or Japanese) suggests that language characteristics may not affect how well each hemisphere does the task but do affect what it is the hemispheres are doing to complete the task. This point may be related to the inconsistency of the bias measure revealed in this series of experiments. Out of the four studies, English speakers revealed a significantly negative bias score (indicating an RH-like strategy in the bilateral condition) only in Experiment 1 and only in the native language condition. Hebrew speakers revealed a significant positive bias score (indicating an LH-like strategy in the bilateral condition) only in Experiment 2 (in RT differences to first and last letters) and Experiment 3. In addition, Luh and Levy (1995) showed that individual differences in bias scores are related to degree of performance asymmetries in the unilateral conditions and concluded that both hemispheres contribute to the processing of stimuli presented bilaterally. If, in addition to these variables, the orthographic characteristics of the native language affect hemispheric strategies, then it seems that, given current knowledge, the bias measure may not be interpreted in a straightforward manner.

The results of the second-language conditions in Experiment 1 and Experiment 3 suggest that the cognitive strategies developed for reading a native language may have long-term implications for the processing of all orthographies. Different orthographies may require different processing allocations between the hemispheres. The data reported here suggest that there is variability in the mode of processing lateralized linguistic stimuli and that this variability is related to the characteristics of the native language of the participants. Kim (1996) showed this variability in one language group (English speakers). He presented vertically aligned trigrams that were composed of pronounceable CVCs, unpronounceable CCCs (e.g., *PGT*), and nonletter symbols (e.g., =, &, %) and found the expected larger FE–LE difference in the LVF for both letter stimuli and the opposite asymmetry (larger FE–LE difference in the RVF than in the LVF) for nonletter symbols. He suggested that hemispheric modes of processing change in response to whether the stimuli are letters. The results of the present experiments contradict the generality of this point and, instead, suggest that hemispheric modes of processing are also sensitive to the characteristics of the language and the manner in which it is represented by the graphemes. More important, these experiments add a dimension to the ways that a specific learned behavior can affect hemispheric processes in a variety of lateralized tasks. These experiments underline the importance of both converging and diverging patterns of performance asymmetries from different populations to the delimitation of the interaction of individual experiences and the genetic functional architecture of higher cognitive functions in the cerebral hemispheres.

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