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Morphological Structure and Hemispheric Functioning: The Contribution of the Right Hemisphere to Reading in Different Languages

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This study examined the relationship between morphological structure of languages and performance asymmetries of native speakers in lateralized tasks. In 2 experiments, native speakers of English (concatenative morphology stem plus affix) and of Hebrew and Arabic (nonconcatenative root plus word-form morphology) were presented with lateralized lexical decision tasks, in which the morphological structure of both words and nonwords was manipulated. In the 1st study, stimuli were presented unilaterally. In the 2nd study, 2 stimuli were presented bilaterally, and participants were cued to respond to 1 of them. Three different indexes of hemispheric integration were tested: processing dissociation, effects of distractor status, and the bilateral effect. Lateralization patterns in the 3 languages revealed both common and language-specific patterns. For English speakers, only the left hemisphere (LH) was sensitive to morphological structure, consistent with the hypothesis that the LH processes right visual field stimuli independently but that the right hemisphere uses LH abilities to process words in the left visual field. In Hebrew and Arabic, both hemispheres are sensitive to morphological structure, and interhemispheric transfer of information may be more symmetrical than in English. The relationship between universal and experience-specific effects on brain organization is discussed.

Keywords: language morphology, Hebrew, Arabic, lexical decision, interhemispheric integration

Half a century of intensive research has revealed that although the left hemisphere (LH) is dominant for most language functions in 99% of right-handers and in the majority (65%) of left-handers, there is widespread variability in the linguistic abilities of the right hemisphere (RH). This variability has been noted in studies of the disconnected RH in split-brain patients (see Zaidel, 1998, for a review); in case reports of the reversal of laterality patterns in aphasia; and in cases of recovery of function believed to reflect RH compensation for a severely damaged LH (Kinsbourne, 1998). It has been suggested (e.g., Kinsbourne, 1998) that the language potential of the RH may be genetically underdetermined and that it may be subject to factors in embryogenesis or postnatal experience. Much research has been done looking at the effects of biological variables, such as sex and handedness (e.g., Eviatar, Hellige, & Zaidel, 1997), on individual differences in patterns of hemispheric specialization. The research reported here focuses on the effects of a specific kind of postnatal experience, specifically, on the structure of the language that the individual uses.

The last few years have seen a large number of studies exploring RH involvement in the processing of discourse aspects of language. Much of this interest is based on the findings from metabolic imaging studies that have revealed extensive RH activations while people are performing linguistic tasks (see Bookheimer, 2002, for a review). Faust et al. have examined RH involvement in syntactic processes (e.g., Faust, Bar-Lev, & Chiarello, 2003). The general findings have been that although the RH is sensitive to message-level processes, all the effects of syntactic manipulations are stronger in the LH. The role of syntactic processes is to compute the structural and thematic relationships between the words in the sentence, so it makes sense to assume that the more highly a language is inflected, the closer the interaction of these syntactic processes is with lexical representation. Thus, the manner in which words are represented in the mental lexicon has implications for the mechanisms involved in comprehension of the message level of sentences. When these underlying representations differ among languages, is it the case that the relative involvement of the cerebral hemispheres differs as well?

Brain imaging studies examining the processing of morphological aspects of language performance have tended to focus on regions of interest in the LH (e.g., Lehtonen, Vorobyev, Hugdahl, Tuokkola, & Laine, 2006). Studies examining Indo-European languages have focused primarily on the representation of morphological knowledge, testing dual-route models versus connectionist, single-route representations in English (e.g., Devlin, Jamison, Matthews, & Gonnerman, 2004; Joanisse & Seidenberg, 2005; Tyler, Stamatakis, Post, Randall, & Marslen-Wilson, 2005; Vannest, Polk, & Lewis, 2005), or on the separability of morphological processing from other aspects of word processing in morphologically richer languages, such as German (e.g., Longoni, Grande, Hendrich, Kastrai, & Huber, 2005) and Italian (Marangolo, Piras, Galati, & Burani, 2004). Studies examining morphological processing in non-Indo-European languages with rich morphological structures have shown RH involvement in word perception, though the RH was not sensitive to inflectional morphological manipula-

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tion, in Hebrew (Palti, Ben-Shachar, Hendler, & Hadar, 2007), and was less sensitive than the LH, in Finnish (Laine, Rinne, Krause, Teras, & Sipila, 1999).

Examinations of the effects of morphology in lateralized paradigms with native speakers of English (Burgess & Skodis, 1993) and French (Koenig, Wetzel, & Caramazza, 1992) have suggested that only the LH is sensitive to the morphological structure of words. However, in Finnish, which is not an Indo-European language and is highly inflected, Laine and Koivisto (1998) found no interaction of performance asymmetries with word morphology. They concluded that both hemispheres of Finnish readers are capable of morpheme-based lexical access, but that this mechanism is more accurate in the LH. A number of studies have explored the underlying representation of words in the lexicon of Semitic languages and have proposed that this representation is different from that of words in Indo-European languages (Feldman, Frost, & Pnini, 1995; Prunet, Beland, & Idrissi, 2000). The present experiments were part of a research plan that takes advantage of some principled differences between Hebrew, Arabic, and English to explore a componential analysis of the reading process in different languages and the effects of different components (visual, orthographic, and morphological demands) on the hemispheric division of labor in reading.

Language-Specific Hemispheric Effects

Arabic, Hebrew, and English use alphabetic orthographies but differ in interesting ways. English is read from left to right, whereas both Arabic and Hebrew are read from right to left. Previously, we have shown that this difference in directionality, affecting lifelong reading habits, has implications for the efficiency with which skilled readers can ignore information on the side from which reading usually begins (Eviatar, 1995) and for performance asymmetries in tasks thought to reflect RH dominance (Eviatar, 1997). Examination of the differences in orthography and phonology relations among the languages, together with the language experience of the participants, revealed (a) that strategies of phonological encoding that are specific to an orthography seem also to be used while reading a second language (Eviatar, 1999) and (b) that the processing of Arabic orthography seems to make different demands on the cognitive system both in beginning (Ibrahim, Eviatar, & Aharon-Peretz, in press) and in skilled readers (Ibrahim, Eviatar, & Aharon-Peretz, 2002). We have suggested that this is because Arabic orthography specifically disallows the involvement of the RH in letter identification, even though the RH of the same participants does contribute to this process in English and in Hebrew (Eviatar & Ibrahim, 2004; Eviatar, Ibrahim & Ganayim, 2004). The grapheme–phoneme relationship in Arabic is very complex, with each phoneme represented by three or four different graphemes, depending on where it appears in the word (beginning, middle, or end) and whether it follows a connecting letter or not. Very different phonemes (such as /t/ and /b/) are represented by the same basic shape, differing only in the number and placement of dots (e.g., /t/ـت and /b/ـب).

We have shown that native Arabic readers respond equivalently to Hebrew and to Arabic when letters are presented in the right visual field (RVF) but make selectively more errors in Arabic than in Hebrew when letters are presented in the left visual field (LVF). In fact, they make as many errors as participants who cannot read Arabic.

The focus of the present research is differences between the languages in morphological structure. In English, which has a concatenative morphology, multimorphemic words are usually created by affixation, a process in which the stem is usually a word itself, and its orthographic integrity is largely preserved. Arabic and Hebrew are characterized by a nonconcatenative, highly productive derivational morphology (Berman, 1978). Most words are derived by embedding a root into a morphophonological word pattern. In both languages, most words are based on a trilateral root and various derivatives that are formed by the addition of affixes and vowels. The roots and phonological patterns are abstract entities, and only their joint combination forms specific words. The core meaning is conveyed by the root, whereas the phonological pattern conveys word-class information. For example, in Arabic, the word *takreem* consists of the root *krm* (whose semantic space includes things having to do with respect) and the phonological pattern ta_ _ ee_. The combination results in the word *honor*. In Hebrew, the word *sifra* consists of the root *sfr* (whose semantic space includes things having to do with counting) and the phonological pattern _i_ _a, which tends to occur in words denoting singular feminine nouns, resulting in the word *numeral.* The letters that make up the root may be dispersed across the word, interdigitated with letters that can double as vowels and other consonants that belong to the morphological pattern.

A number of psycholinguistic studies (Berent, 2002; Deutsch, Frost, & Forster, 1998; Feldman et al., 1995; Frost & Bentin, 1992; Frost, Forster, & Deutsch, 1997) have explored the effects of the morphology and orthography of Hebrew on lexical access and the structure of the mental lexicon. Two conclusions from these studies are especially relevant to the present study. The first is that the nonconcatenative and agglutinative morphological structure of Hebrew, together with the distributional properties of abstract word forms, results in the inclusion of subword morphological units in the mental lexicon of Hebrew speakers. The second is that morphologically complex Hebrew words cannot be read via incremental parsing (sequentially, letter by letter). This last claim converges with the conclusions of Eviatar (1999, Experiment 4), who showed that nonwords are processed sequentially in both visual fields by English speakers but in neither visual field by Hebrew speakers and hypothesized that this is because Hebrew nonwords cannot be read sequentially. Farid and Grainger (1996) suggested the same for the reading of Arabic. They 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 best recognition for both prefixed and suffixed words, whereas in Arabic, prefixed words result in best recognition from leftward fixations, and suffixed words result in best recognition from rightward initial fixations. They suggested that this pattern 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" (p. 364), that is, after extraction of the root. Berent (2002) has also concluded that in Hebrew, "speakers decompose the root from the word pattern in on-line word identification" (p. 335). Prunet et al. (2000) reported a case study of an Arabic–French agrammatic patient who showed identical deficits in the two languages, except for a specific type of error, metathesis, in which he modified the order of the root consonants, with the vowel patterns remaining intact, in Arabic and not in French. They interpreted this finding as reflecting the manner in which words are stored in the mental lexicon in the two languages: whole words plus affixes in French and roots plus word patterns in Arabic.

The Present Study

The hypotheses tested here revolved around two related foci. The first focus is the relationship between the morphological structure of a language and performance asymmetries in a lateralized lexical decision task. The second focus is three indexes of hemispheric functioning that are informative about interhemispheric integration. In the two experiments described below, native speakers of English, Hebrew, and Arabic were presented with a lateralized lexical decision task, in which the morphological structure of both words and nonwords was systematically manipulated. In the first study, stimuli were presented unilaterally (in one visual field on each trial). In the second study, two stimuli were presented bilaterally, and participants were cued to respond to one of them. This design allowed us to test three different indexes of hemispheric integration: the processing dissociation, the effects of distractor status, and the bilateral effect. These are described in detail below.

The Processing Dissociation

The processing dissociation is an interaction between a stimulus variable (in our case, lexicality or morphological complexity) and the visual field to which it was presented. The interpretation of such a pattern rests on the reasoning that if the stimulus variable affects responses in one visual field and not the other, we have evidence for different and independent processes in the two hemispheres. Thus, effects of stimulus lexicality (word vs. nonword) or morphological complexity, demonstrated in one visual field but not the other, will support the hypothesis that each stimulus is processed by the hemisphere contralateral to the stimulated visual field. For example, if Koenig et al. (1992) were correct in suggesting that only the LH is sensitive to morphological structure, we should see the effects of this variable in the RVF but not in the LVF.

Distractor Status

In the second study, we used bilateral versions of the lexical decision task. Here, participants are presented with two stimuli on each trial and are required to ignore one and to make a lexical decision on the other. We can examine the effects of the lexical or morphological effect of the distractor (the stimulus to be ignored) on the response to the target. The logic is the following: If LVF stimuli are processed independently by the RH, then the lexical status or morphological complexity of the distractor presented to the LH should not affect performance. However, if the RH draws upon LH resources to perform the task, we will see an effect of the distractors. Iacoboni and Zaidel (1996) found such an effect in English for words but not for nonwords. They concluded that this is evidence that the RH can reject nonwords independently but that it draws upon LH processes to accept words.

The Bilateral Effect

The third measure of interhemispheric integration results from comparison of the unilateral and the bilateral conditions in equivalent language groups. Boles (1990) reported that performance asymmetries are larger when stimuli are presented bilaterally (with a cue marking the side to which to respond) than when they are presented unilaterally. He proposed that this "bilateral effect" occurs because bilateral presentation of different stimuli to homologous areas of the two hemispheres disrupts communication between them. Iacoboni and Zaidel (1996) have suggested that the degree of the bilateral effect allows assessment of interhemispheric interactions for different types of stimuli. That is, processes that are performed independently by each hemisphere should not result in different performance asymmetries with either unilateral or bilateral presentations, whereas processes that require interhemispheric cooperation should result in larger performance asymmetries with bilateral presentation.

This comparison will also allow a test of the hypothesis that reading scanning habits have a larger effect on performance asymmetries with bilateral presentation than with unilateral presentation (Eviatar, 1995). Two hypotheses resulted in contradictory predictions. Iacoboni and Zaidel's (1996) hypothesis predicted that the size of the bilateral effect will vary with the other indexes of hemispheric involvement, when conditions in which there is hemispheric independence will not show a difference, whereas conditions suggesting interhemispheric cooperation will show this effect. Eviatar's (1995) hypothesis predicted that Hebrew and Arabic tests will result in larger performance asymmetries with bilateral than with unilateral presentations across all of the conditions. This hypothesis was based on findings that when two different stimuli are presented bilaterally and participants are asked to ignore one of them, Hebrew readers find it harder to ignore a stimulus in the RVF than one in the LVF, and English readers show the opposite pattern. This finding was interpreted as reflecting an automatic transfer of attention to the side at which reading usually begins (the right for Hebrew readers and left for English readers) and the necessity to disengage from the distractor before processing the target in the other visual field. Thus, Hebrew readers and Arabic readers should show a larger RVF advantage with bilateral presentations, because targets in their LVF will only be processed after disengagement from the RVF.

Study 1: Unilateral Presentations of the Lexical Decision Task

Method

Participants

The participants were 60 students at Haifa University, 20 in each native language group. The native English speakers were recruited from the summer overseas program. All were American and were paid for their participation. The native Hebrew and Arabic speakers were all students at Haifa University. Most of them completed the experiments for course credit, with some receiving payment instead. All were right-handed, were neurologically normal, and had normal or corrected vision.

Stimuli

We compiled three lists of 80 words and 80 nonwords, one in each language. Of the words, 40 were morphologically simple, and 40 were morphologically complex. In Hebrew and Arabic, morphological complexity was operationalized as the transparency of the root, such that words derived from generative roots were considered complex, and words in which the roots are not generative (they appear only in that form) were considered simple.[1] In English, morphologically complex words were derivations.

The lists were equated on the average frequency of the words, number of letters, and initial letters. For the English list, we used Kucera and Francis's (1967) frequency counts; the mean frequencies of the complex words and the simple words were 37.02 and 38.6, respectively. There are no frequency norms in Hebrew and Arabic, and we did not pretest our particular lists. However, none of the stimuli are infrequent or uncommon words. Nonwords were also morphologically manipulated. Morphologically simple nonwords in English were derived from the simple words by changing one or two letters, and complex nonwords were illegal combinations of real morphemes (e.g., gapty). In Hebrew and Arabic, morphologically simple nonwords were derived from the simple words by changing one or two letters, and complex nonwords were constructed from nonexistent roots embedded in legal word forms. The stimuli are listed in the Appendix.

Procedure

The participants were tested individually. The stimuli were presented on a Silicon Graphics Workstation. On each trial, the sequence of events was the following: A 1,000-Hz tone sounded for 100 ms to alert the participant that the trial was beginning. Then the fixation cross was presented for 100 ms. The stimuli were presented for 180 ms horizontally, with their inner edge 2° of visual angle offset from fixation, either in the LVF or the RVF. English stimuli were in the Times New Roman font, the Hebrew stimuli were in Guttman Miryam, and the Arabic stimuli were in MCS Madinah S_U normal, all point size 22. The longest words subtended 2.5° of visual angle. All appeared as white letters on a gray screen. The stimuli were followed by a pattern mask that remained onscreen until the participant had responded or 3 s had passed. The screen was blank for 2 s, and then the next trial began. The participant responded on the keyboard by pressing the up arrow if the stimulus was a real word and pressing the down arrow if it was not.

Results

We measured median reaction time (RT) and percentage errors. Trials in which RT was shorter than 100 ms or longer than 3,000 ms were excluded from analysis. None of the groups showed speed–accuracy trade-offs. For Hebrew and Arabic speakers, there was no correlation between response time and error ($p > .05$). For English speakers, the correlation was $r(19) = .23$, $p < .05$. This is a positive relationship, showing that fast responders made fewer errors.

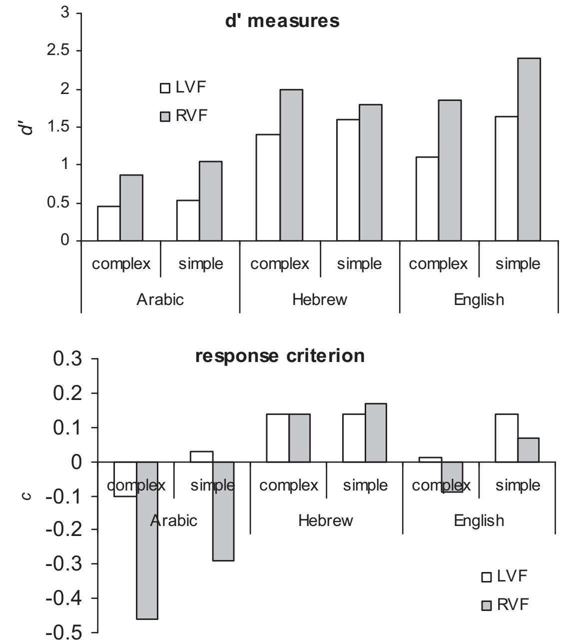

Figure 1. Signal detection measures in Experiment 1: unilateral presentations. c = criterion; LVF = left visual field; RVF = right visual field.

Because error rates in some conditions were high, we performed a signal-detection analysis to make sure that participants were sensitive to the difference between words and nonwords in all of the conditions. We computed the sensitivity measure d' as the difference between the z scores for the probability of hits (for words) and for false alarms (for nonwords) and computed the criterion as $c = z[p(\text{hits})] + z[p(FA)]/2$. We used correction computations for probability values of 1 (later changed to $1/[2N]$) and 0 (later changed to $1 - 1/[2N]$) on the basis of suggestions of Macmillan and Creelman (1990). These data are presented in Figure 1. It can be seen that all of the participants showed higher sensitivity to the lexicality status of the stimuli in the RVF than in the LVF: Arabic speakers, $F(1, 19) = 8.04$, $p < .05$, $\eta_p^2 = .29$; Hebrew speakers, $F(1, 19) = 8.76$, $p < .01$, $\eta_p^2 = .32$; English speakers, $F(1, 19) = 23.58$, $p < .001$, $\eta_p^2 = .55$. All of the mean d' scores were significantly larger than 0. Thus, all of the participants showed a pattern indicating LH specialization for this linguistic task and better-than-chance performance in all of the conditions. The criterion measure shows that Arabic speakers had a significant "yes" bias in the RVF, whereas their responses in the LVF were unbiased. Hebrew speakers showed a "no" bias in the RVF for all stimuli and in the LVF for morphologically simple stimuli. English speakers were unbiased in all of the conditions.

Native Language Effects

Separate three-way analyses of variance were performed on the median RTs and percentage errors of each language group. The

[1] This is based on the finding of Feldman, Frost, and Pnini (1995) that skilled Hebrew readers can detach a word form more quickly from a generative root than from a nongenerative root. That is, they can divide the word into its root and word-form morphemes more easily when the root is generative than when it is not.

Table 1
Statistical Effects for Median Reaction Time and % Errors of Lexicality, Morphology, and Visual Field in Each Language Group

Effect	RT			% error		
	English	Hebrew	Arabic	English	Hebrew	Arabic
Lex × Morph × VF	*ns*	*ns*	*ns*	*ns*	3.25, $p = .087$, $\eta_p^2 = .15$	*ns*
Lex × VF	4.26, $p < .053$, $\eta_p^2 = .18$	*ns*	4.26, $p < .053$, $\eta_p^2 = .18$	*ns*	*ns*	18.46, $p < .0001$, $\eta_p^2 = .49$
Lex × Morph	*ns*	*ns*	7.07, $p < .05$, $\eta_p^2 = .27$	5.30, $p < .05$, $\eta_p^2 = .22$	*ns*	5.91, $p < .06$, $\eta_p^2 = .24$
Morph × VF	6.89, $p < .05$, $\eta_p^2 = .27$	*ns*	*ns*	*ns*	3.0, $p = .099$, $\eta_p^2 = .14$	*ns*
Lex	28.79, $p < .001$, $\eta_p^2 = .60$	14.77, $p < .001$, $\eta_p^2 = .44$	15.45, $p < .001$, $\eta_p^2 = .74$	*ns*	4.86, $p < .05$, $\eta_p^2 = .20$	5.81, $p < .05$, $\eta_p^2 = .23$
Morph	*ns*	*ns*	*ns*	32.72, $p < .0001$, $\eta_p^2 = .52$	*ns*	*ns*
VF	6.88, $p < .05$, $\eta_p^2 = .27$	*ns*	*ns*	21.35, $p < .0001$, $\eta_p^2 = .53$	6.66, $p < .05$, $\eta_p^2 = .26$	7.59, $p < .05$, $\eta_p^2 = .29$
Mean error (%)				22	22.5	36.6

Note. $df = 1, 19$. RT = reaction time; Lex = lexicality; Morph = morphology; VF = visual field.

results are presented in Table 1. The table highlights the similarities and differences between asymmetry patterns in the different languages. Reflecting the sensitivity measures, all three groups revealed the expected RVF advantage in accuracy, with the English language group showing this in RT as well. In addition, all three groups showed an effect of lexicality, with words being responded to faster than nonwords, with the Hebrew and Arabic speakers showing a word advantage in errors as well. Thus, overall, performance in the lexical decision task reflected LH specialization for the task and a word-superiority effect in the three languages. The higher order interactions are discussed separately for each group.

English

The cell means of the Lexicality × Morphology × Visual Field conditions are illustrated in the top panels of Figure 2. The results for the English-language group were clear cut. It can be seen that the three-way interactions in both RT and errors were not significant, because the patterns were similar for words and nonwords. In RT, the simple main effect of morphology was significant only in the RVF for both words, $F(1, 19) = 13.43$, $p < .005$, $\eta_p^2 = .41$, and nonwords, $F(1, 19) = 9.46$, $p < .01$, $\eta_p^2 = .33$. As listed in Table 1, in RT, both the Lexicality × Visual Field interaction and the Morphology × Visual Field interaction were significant. Morphology had no main effect, but the main effects of both lexicality and visual field were significant. Thus, the manipulation of lexicality and of morphology resulted in a processing dissociation, suggesting independent processing in the two hemispheres for words and for nonwords.

In errors, the Lexicality × Morphology interaction was significant, because morphological complexity affected responses only to nonwords, to the same extent in both visual fields: LVF, $F(1, 19) = 13.51$, $p < .005$, $\eta_p^2 = .42$; RVF, $F(1, 19) = 19.59$, $p < .001$, $\eta_p^2 = .49$.

Hebrew

The cell means for the Hebrew speakers are illustrated in the middle panels of Figure 2. The RT data show two effects: a main effect of lexicality (see Table 1) and a simple main effect of morphology only for words in the RVF, $F(1, 19) = 6.74$, $p < .05$, $\eta_p^2 = .26$, with complex words being responded to more quickly than simple words.

In the error data, the three-way interaction between lexicality, morphology, and visual field approached significance. The main effects of lexicality and of visual field are significant, as is a simple main effect of morphology, only for nonwords and only in the LVF, $F(1, 19) = 8.87$, $p < .01$, $\eta_p^2 = .34$, with fewer errors being made on simple nonwords than on complex nonwords. These data are similar to those for the English speakers, in that RT measures revealed sensitivity to morphological complexity of words only in the RVF but differ from those for the English speakers, in that the error measure revealed this sensitivity only for nonwords in the LVF.

Arabic

The cell means of the Arabic speakers are illustrated in the bottom panels of Figure 2. As listed in Table 1, in RT the two-way interactions between lexicality and visual field and Lexicality × Morphology were significant, together with the main effect of lexicality. In RT, Arabic speakers showed an RVF advantage, $F(1, 19) = 4.37$, $p = .05$, $\eta_p^2 = .19$, for words and showed no advantage for nonwords. The cell means data showed that for words, the simple main effect of morphology was significant only in the LVF, with complex words resulting in faster responses than simple words, $F(1, 19) = 4.33$, $p < .05$, $\eta_p^2 = .19$; for nonwords, there was a trend, $F(1, 19) = 3.33$, $p = .08$, $\eta_p^2 = .15$, for the opposite effect in the RVF, in which complex nonwords took longer to reject than simple nonwords.

The error data showed very similar effects, with significant interactions between lexicality and visual field and lexicality and morphology, a significant main effect of lexicality, and a significant main effect of visual field. The advantage of simple over complex nonwords in the RVF was significant as well, $F(1, 19) = 7.67$, $p < .05$, $\eta_p^2 = .39$. Again, the RVF advantage for words was significant, $F(1, 19) = 18.94$, $p < .01$, $\eta_p^2 = .50$, whereas for nonwords it was not. Thus, like the Hebrew speakers,

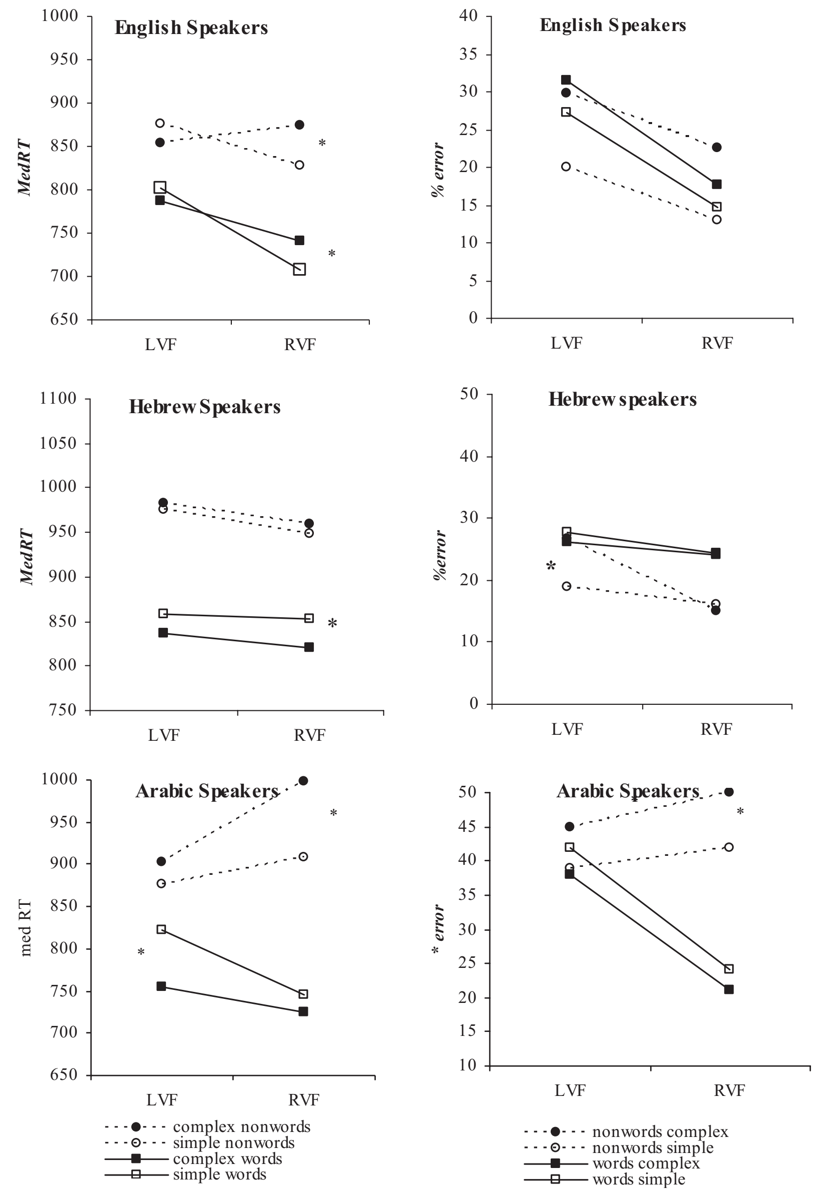

Figure 2. Effects of morphology, lexicality, and visual field in each language group with unilateral presentations. MedRt = median reaction time; LVF = left visual field; RVF = right visual field.

the Arabic speakers showed effects of morphological complexity differently for words and for nonwords, and they showed these effects in both visual fields.

Discussion

The data reveal both similarities and differences in the patterns evinced by native speakers of different languages performing the test in those languages. The similarities reflect design characteristics of the human brain, irrespective of the characteristics of the languages. Thus, all of the participants revealed a significant RVF advantage, reflecting LH specialization for this linguistic task. In addition, all the participants showed an effect of lexicality, which reflected that words and nonwords are processed differently in all three languages.

The differences in patterns among the three language groups reflect the interaction of specific language structure and hemispheric abilities (Eviatar et al., 2004). Here we manipulated morphological complexity, which is manifested very differently in English and in the Semitic languages. We see that in English, when there is an effect of the morphology of the stimulus, monomorphemic words and nonwords are always processed faster (in the RVF) and more accurately (in both visual fields) than are bimorphemic words and nonwords. In both Hebrew and Arabic, we see an opposing effect of morphological complexity for words and for nonwords. Complex words—which we defined as those having a transparent, or generative, root—were recognized as words faster and more accurately in both languages (in the RVF in Hebrew and in the LVF in Arabic). Complex nonwords, which are nonexistent roots embedded in real word forms, were harder to reject than were simple nonwords, which did not contain an easily recognizable word form (in the LVF in Hebrew and in the RVF in Arabic). Thus, morphological transparency facilitated the recognition of words and interfered with the recognition of nonwords. This result is congruent with the findings reported in the introduction, which suggested that sublexical elements are represented in the mental lexicons of readers of Hebrew (Feldman et al., 1995) and of Arabic (Prunet et al., 2000).

In terms of hemispheric functioning, the RT data for the English speakers replicated the results of Burgess & Skodis (1993) and Koenig et al. (1992) by showing differential RTs for complex and simple stimuli only in the RVF. These authors interpreted their findings as indicating that the LH is sensitive to the morphological structure of stimuli, whereas the RH is not. The error scores of the English speakers presented an ambiguous pattern: It could result from equal sensitivity in the two hemispheres to morphological complexity or from LH sensitivity, with stimuli presented to the LVF (RH) being processed by the LH after callosal transfer (Zaidel, 1983). The present results do not differentiate between these hypotheses.

The results for the Hebrew and the Arabic speakers differed in terms of performance asymmetry patterns. Although the same effects of morphology on words and nonwords were shown, the distribution of these effects in the visual fields was different (see Figure 2). In RTs, the pattern for words in Hebrew was similar to the pattern for words in English: Morphology affected responses in the RVF and not in the LVF. For nonwords, these participants showed an effect of morphology in errors only in the LVF. The Arabic speakers also showed different asymmetry patterns in RT and in errors, with an effect on RT in words in the RVF and an effect on errors in nonwords in the LVF. These patterns are difficult to interpret, but at least they suggest that morphology affected processing of words and of nonwords differently in the cerebral hemispheres of these participants. The results are also consistent with the hypothesis, raised in the introduction, that both hemispheres are sensitive to morphological structure in these Semitic languages.

In summary, the findings of the unilateral experiments support the hypothesis that when English speakers perform the lexical decision task in English, the LH is more sensitive to the morphological status of both words and nonwords than is the RH. In addition, the findings suggest more interhemispheric interactions in the task among the speakers of Hebrew and of Arabic. In Study 2, we examined more closely the possible forms of interhemispheric integration that we may be seeing here.

Study 2: Bilateral Presentations of the Lexical Decision Task

Method

Participants

The participants were 60 students at Haifa University sampled from the same populations described for Study 1. None had participated in the first study. The data of 2 Arabic-speakers were excluded because of experimenter error, so this group included 18 participants instead of 20.

Stimuli

We used the same stimuli as those used in Study 1. Each target stimulus was paired with another stimulus, as a distractor, from each of the stimulus categories. For example, a target that was a morphologically complex word was paired with another morphologically complex word, a simple word, a morphologically complex nonword, or a morphologically simple nonword. Thus, the design was identical to that of the experiments described in Study 1, except for the addition of the variable distractor. It had 2 levels, had the same lexical status as the target (a word for words and a nonword for nonwords), and had a different lexical status than the target (nonwords for words and words for nonwords).

Procedure

The procedure was identical to that in the experiments in Study 1, except that two stimuli appeared in each trial, one in each visual field. One of the stimuli was underlined, indicating that it was the target and that the other stimulus was to be ignored.

Results

We computed the correlations between median RT and percentage error to test for speed–accuracy trade-offs. Hebrew speakers revealed a positive relationship, $r(19) = .45$, $p < .05$, indicating that participants who responded more slowly also made more errors. English speakers did not reveal a relationship between these measures, whereas Arabic speakers showed a significant trade-off between speed of responses and percent errors, $r(17) = -.62$, $p < .01$, indicating that participants who responded more slowly made fewer errors.

As in Study 1, we computed signal-detection measures to check if lexical decision was better than chance. These data are illustrated in Figure 3. For Hebrew speakers and English speakers, all of the d' measures were significantly different from 0. For Arabic speakers, this was true for stimuli presented to the RVF; in the LVF, however, d' for complex words was only marginally different from 0, $t(18) = 1.88$, $p = .077$, and for simple words it was essentially 0. It can be seen that all of the participants showed an RVF advantage: Arabic speakers, $F(1, 18) = 16.22$, $p < .001$, $\eta_p^2 = .47$; Hebrew speakers, $F(1, 19) = 31.77$, $p < .0001$, $\eta_p^2 = .62$; English speakers, $F(1, 19) = 19.12$, $p < .005$, $\eta_p^2 = .50$. The response criterion measure revealed that all of the participants showed a "no" bias in the LVF and a "yes" bias in the RVF.

Replication of Study 1

Figure 4 illustrates the patterns within each language group. As can be seen by comparing these patterns with those in Figure 2, our major finding was replicated. The English speakers again showed effects of morphological complexity only in the RVF, the Hebrew speakers revealed these effects in both visual fields, and the Arabic speakers revealed a significant effect in the LVF for nonwords in RT.

Effects of Distractor Type

The data from these experiments were gathered to see if the lexical status of the distractor affected lexical decisions on the

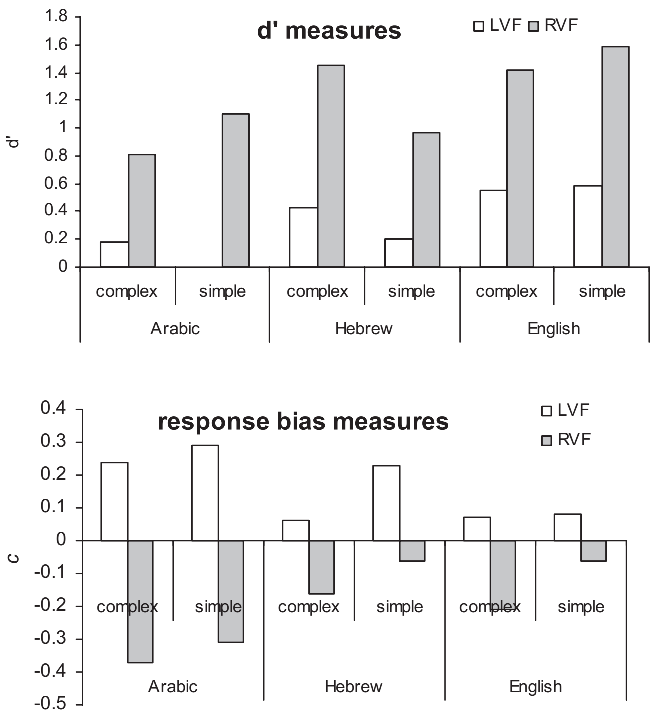

Figure 3. Signal detection measures in Experiment 2: bilateral presentations. c = criterion; LVF = left visual field; RVF = right visual field.

targets. To test this directly, we performed analyses of the simple main effect of distractor type in each of the Lexicality × Morphology × Visual Field conditions for each language group. The results of these analyses are presented in Table 2.

Recall that a significant effect of distractor type is interpreted as indicating that the hemisphere contralateral to the target visual field drew upon the resources of the other hemisphere while processing the target. Several patterns can be discerned from this table. The first is that the only significant effect was in the LVF, for complex words and for English speakers. There were marginal effects in the LVF for complex nonwords in this group, as well. These data replicated the finding reported by Iacoboni and Zaidel (1996) with English speakers. The speakers of the Semitic languages did not show significant effects of distractor status, although the Hebrew speakers showed marginal effects for both simple (in the LVF) and complex (in the RVF) words and for simple nonwords (in the LVF). Given our reluctance to interpret null effects, we can summarize and say that this measure of interhemispheric communication revealed that for English speakers, responses to LVF stimuli were influenced by the characteristics of the distractor presented in the RVF but not vice versa. This finding suggests that the RH drew on LH resources to perform lexical decisions upon both nonwords and complex words; it is consistent with the hypothesis that the LH performed independently. The patterns for Hebrew speakers may point to more symmetrical interhemispheric interactions, with both the LH and the RH influenced by the characteristics of the distractor presented to the other hemisphere, suggesting interhemispheric effects. We do not have positive evidence for interhemispheric effects in the Arabic speakers, as the effect of distractor status was not significant in any condition. The analysis of the bilateral effect may allow us to distinguish between hemispheric interaction and hemispheric independence.

The Bilateral Effect

Analysis of these data without the factor of type of distractor allows us to examine the effects of bilateral presentation on the performance patterns revealed in Study 1. Boles (1990) suggested that the difference between performance in the two visual fields is influenced by presentation mode, such that processes that require communication between the hemispheres will result in larger visual field differences with bilateral than with unilateral presentations. Thus, comparison of the magnitude of visual field differences in the Lexicality × Morphology × Visual Field conditions can indicate hemispheric independence or hemispheric interdependence. Recall also that Eviatar (1995) predicted that visual field differences would be larger with bilateral presentations than with unilateral presentations among participants who read from right to left (as in the Semitic languages) in any case, as a result of attentional habits.

To test these hypotheses, we computed the visual field difference (LVF minus RVF for both median RTs and percent errors) in each Lexicality × Morphology condition in all the Language × Presentation Mode groups. We computed the simple main effect of presentation mode (unilateral versus bilateral) in each of the Lexicality × Morphology conditions for the three language groups. The results of these analyses, together with the means tested, are presented in Table 3. It can be seen that Arabic speakers and Hebrew speakers showed a significant bilateral effect for words, with the Hebrew speakers showing this effect also for complex nonwords. Eviatar's (1995) hypothesis was supported by the data: Visual field asymmetries in the Arabic and Hebrew language groups were significantly larger in the bilateral condition than in the unilateral condition, and there was no effect for the English speakers. However, recall that Iacoboni and Zaidel (1996) had predicted that the bilateral effect would occur only as a result of interhemispheric integration. Consistent with this prediction, our other indexes—the processing dissociation and the effects of distractor status—suggested that among English speakers, the RH calls upon LH resources for word stimuli but not necessarily for nonword stimuli. It can be seen that the bilateral effect was larger for words than for nonwords for these participants. In summary, the strength of the bilateral effect suggests hemispheric interdependence and integration among Arabic speakers and Hebrew speakers and not among English speakers.

Discussion of Studies 1 and 2

The goal of this research was to use three behavioral measures of performance asymmetries in a divided visual field paradigm to explore the involvement of the RH in reading in different languages. Specifically, we examined the effects of morphological complexity of words and pseudowords in a lexical decision task. The results revealed a pattern of similarities and differences in the processing of English, Hebrew, and Arabic.

In English, we see that the recognition of words and pseudowords is affected in the same way by morphological complexity, with monomorphemic words and nonwords derived from

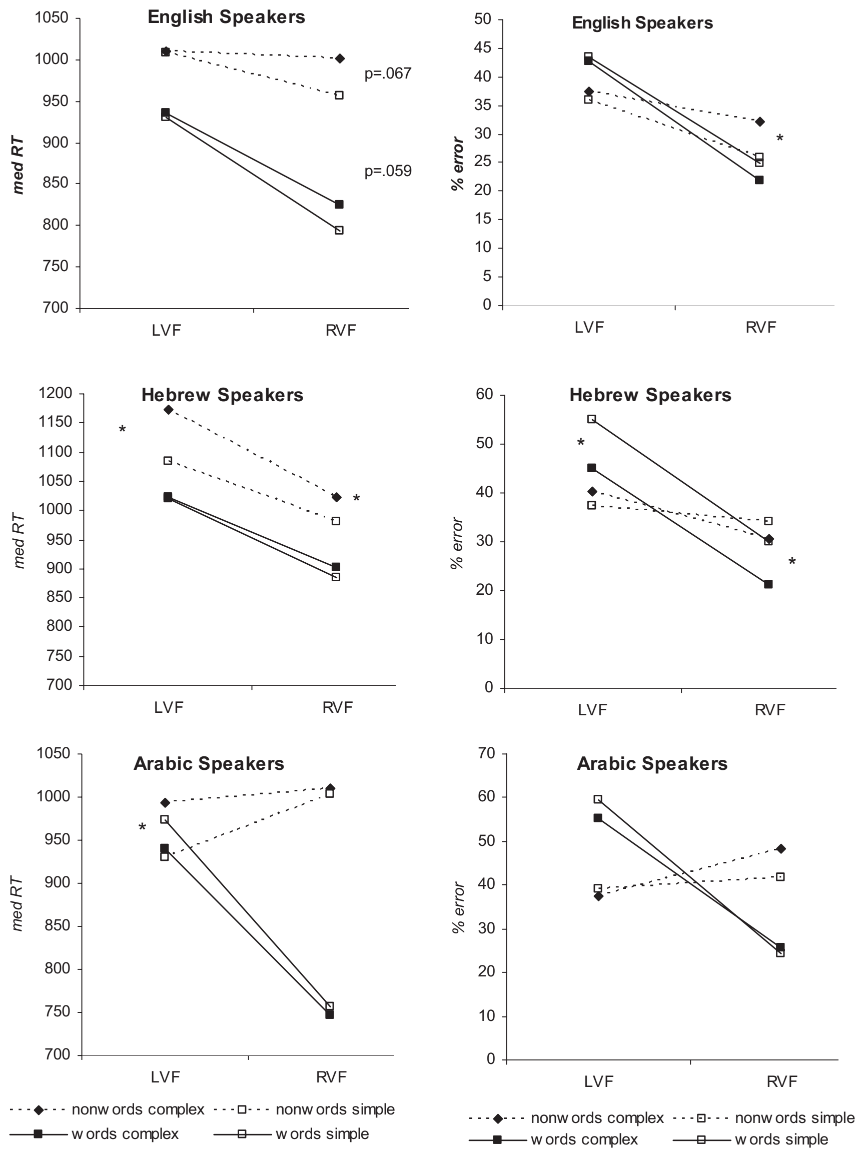

Figure 4. Effects of morphology and visual field in each language group with bilateral presentations. med RT = median reaction time; LVF = left visual field; RVF = right visual field.

them being easier to recognize than are bimorphemic words or multimorphemic nonwords. Our data support the hypothesis that the RH of English speakers is not sensitive to morphological complexity. The RT data from Study 1 (replicated as marginal effects in Study 2) presented a processing dissociation, showing an effect of morphological complexity on RTs only in the RVF. The accuracy data from that study were ambiguous, as the effect of morphological complexity was equal in the two visual fields. The data from Study 2 solved this ambiguity by showing that processing of targets in the LVF (RH) was affected by distractors in the RVF (which were seen first by the LH). Although the bilateral effect was not significant for this group (see Table 3), the means showed that visual field asymmetry was almost always larger in the bilateral condition than in the unilateral condition and that this difference was larger for words than for nonwords. Thus, two out of the three measures of hemispheric functioning suggested that the model that fits the lexical decision process in English is hemispheric independence for the LH and interhemispheric communication and cooperation in the processing of targets presented to the RH.

For Arabic speakers, and to a smaller extent for Hebrew speakers, we see opposite effects of morphological complexity for words and for nonwords. We defined complex words in Arabic as those in which the root and word-form structure were transparent, making them more “unpackable.” This characteristic resulted in faster responses to these stimuli than to words in which the root structure was not apparent; this effect was stronger in the LVF in both studies (see Figures 2 and 4). For nonwords, morphological “unpackability,” or transparency, resulted in slower response times in the RVF in Study 1. We did not see any effects of distractor status

Table 2
Statistically Significant Simple Main Effects of the Lexical Status of the Distractor (Same or Different) on the Reaction Time and Error Rates of Lexical Decisions on Targets in Study 2

	Nonwords				Words			
	Complex		Simple		Complex		Simple	
Target	MedRT	% error	MedRT	% error	MedRT	% error	MedRT	% error
				Arabic speakers (df = 1, 17)				
LVF	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
RVF	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
				Hebrew speakers (df = 1, 19)				
LVF	*ns*	*ns*	*ns*	$F = 3.24$, $p = .08$, $\eta_p^2 = .15$	*ns*	$F = 3.68$, $p = .07$, $\eta_p^2 = .16$	*ns*	*ns*
RVF	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	$F = 3.63$, $p = .07$, $\eta_p^2 = .16$	*ns*
				English speakers (df = 1, 19)				
LVF	$F = 3.88$, $p = .063$, $\eta_p^2 = .17$	$F = 3.58$, $p = .07$, $\eta_p^2 = .02$	*ns*	*ns*	$F = 6.88$, $p < .05$, $\eta_p^2 = .27$	*ns*	*ns*	*ns*
RVF	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Note. MedRT = median reaction time; LVF = left visual field; RVF = right visual field.

in this group in either visual field, so we cannot interpret these null effects. However, the bilateral effect was significant for both simple and complex words. Recall that Boles (1990) and Iacoboni and Zaidel (1996) interpreted this effect as reflecting interhemispheric transfer of information. Two out of the three measures we used supported the following model for reading in Arabic: The LH is sensitive to the structure of pseudowords, because we see an effect of morphological complexity only when a legal word form makes a nonword harder to recognize as such. The RH is sensitive to the root structure of words, as words with transparent, or generative, roots are identified faster than are words without such structure. The pattern for words was different from the one shown by English speakers, suggesting bilateral involvement in the lexical decision task, and the pattern for nonwords was similar to the one shown by English speakers, suggesting hemispheric independence. The very high error rates in the LVF, together with our previous findings of RH deficits specific to orthographic processing in Arabic, converged with the conclusion that we are not seeing independent RH processing of words. We are now examining the sensitivities of the RH of Arabic speakers when they are reading other languages.

For Hebrew speakers, the patterns are somewhat less clear cut. The unilateral presentation condition revealed only effects of lexicality and a morphological complexity effect for words (in which, as for the Arabic speakers, complex words with a transparent root structure were recognized faster than were simple words with a morphologically opaque structure). Given that none of these effects interacted with visual field of presentation, we were not able to interpret these patterns in terms of hemispheric functioning. The bilateral conditions were somewhat more revealing. As shown in Table 2, there are trends suggesting sensitivity to the lexical status of the distractor in both visual fields, and as shown in Table 3, the bilateral effect was significant for all words and, in RT, also for complex nonwords. These data support a model in which both hemispheres participate in lexical decisions in Hebrew, with interhemispheric communication going both from left to right and from right to left.

In summary, the data reveal somewhat different patterns of hemispheric functioning in a lateralized lexical decision task that were a function of the language of the test. In previous reports, we have shown that some systematic differences among native speakers and readers of different language groups are insensitive to the language of the test (Eviatar, 1999) and that some are specific and change when bilinguals take the test in their different languages (Eviatar et al., 2004). These differences reflect an interaction between the processes necessary to perform the task in each language (e.g., syllable identification in Eviatar, 1999, or letter identification in Eviatar et al., 2004) and the lateralization of the functional architecture of these processes. That is, the components of reading a written word in different languages (e.g., recognizing the letters making up the word, accessing or assembling the phonological form of the word, and accessing the meaning of the word) can make different demands on the reading system. These different demands may then be differently lateralized. Given the structure of the languages used here, we defined morphological complexity differently in the three language conditions. We cannot know yet whether the different models of interhemispheric interaction that were proposed above for the three different languages arise from the differences in language structure or from differences in reading strategy favored by readers of the different languages. That is, if readers of Hebrew use processes in both hemispheres to read both words and nonwords in Hebrew, do they do so when they

Table 3
Effects of Presentation Mode (Unilateral or Bilateral) on Visual Field Asymmetries (LVF Minus RVF) for Morphologically Simple and Complex Words and Nonwords in Arabic, Hebrew, and English

Language		Nonwords		Words	
		Complex	Simple	Complex	Simple
Arabic ($df = 1, 36$)					
	RT (ms)	*ns* bi = −22 uni = −97	*ns* bi = −78 uni = −33	$F = 5.15$, $p < .05$ bi = 214 uni = 30	$F = 3.98$, $p = .05$ bi = 229 uni = 77
	% error	*ns* bi = −11 uni = −5	*ns* bi = −2 uni = −2	$F = 3.46$, $p = .07$ bi = 31 uni = 17	$F = 3.49$, $p = .07$ bi = 34 uni = 17
Hebrew ($df = 1, 38$)					
	RT (ms)	$F = 8.47$, $p < .01$ bi = 149 uni = 23	*ns* bi = 104 uni = 27	$F = 4.29$, $p < .05$ bi = 120 uni = 16	$F = 10.14$, $p < .005$ bi = 135 uni = 7
	% error	*ns* bi = 9 uni = 13	*ns* bi = 2 uni = 4	$F = 8.46$, $p < .01$ bi = 23 uni = 2	$F = 12.77$, $p < .001$ bi = 24 uni = 3
English ($df = 1, 38$)					
	RT (ms)	*ns* bi = 10 uni = −19	*ns* bi = 53 uni = 47	*ns* bi = 112 uni = 47	*ns* bi = 136 uni = 93
	% error	*ns* bi = 5 uni = 8	*ns* bi = 10 uni = 7	*ns* bi = 20 uni = 14	*ns* bi = 18 uni = 13

Note. The means that were compared are listed in each cell. Shaded cells signify significant or marginally significant differences between unilateral and bilateral presentations. RT = reaction time; bi = bilateral presentation; uni = unilateral presentation.

read English as well? That is, does this model describe how anyone would read Hebrew, or does it characterize only those people who learned to read Hebrew as their first language? We are examining this question in our lab.

The results of this study show that performance asymmetries in a lexical decision task can reveal universal characteristics of the process of reading. They are also sensitive to the specific demands made upon this process by languages with different orthographies and morphological structures.

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(*Appendixes follow*)

Appendix

The Stimuli

Table A1
English Stimuli

Five-letter complex words	Six-letter complex words		Five-letter complex nonwords	Six-letter complex nonwords	
actor	singer	unfair	reday	maltor	sinder
input	heroic	prayer	reton	arting	sapred
unwed	saying	poster	sunly	dogist	urning
voter	verbal	reform	firty	ballic	pulter
usage	useful	refund	armen	hornal	vister
lucky	ironic	upward	vater	hatage	imseen
lover	hatred	inside	landy	inbear	windly
sadly	beaten	insane	poomy	intame	wepter
madly	bakery	search	inspy	inchor	dinter
owner	wooden	recall	baral	lampen	eggely
artist	worker		gapty	litful	pilker
	leader			liping	
	safety			relope	
	ending			soupen	
	living			unwasp	
	golden			unraim	
	farmer			seaper	
	driver			operer	
	dancer				
Five-letter simple words	**Six-letter simple words**		**Five-letter simple nonwords**	**Six-letter simple nonwords**	
ocean	engine	league	abent	ufgine	farble
agent	violin	utopia	doyak	gealth	benslo
dress	virgin	potato	amale	wanget	donkle
radio	motive	poodle	smage	dittle	adeast
idiot	battle	domain	leard	udoryp	iglipe
apple	advice	dollar	avort	hamage	lainth
lemon	wealth	accent	bemin	umtado	likcen
saint	heaven	genius	icrog	ansoct	rupait
bread	rabbit	sponge	oplep	liolin	
mouse	legend		idace	leerus	
image	window		ukint	wottle	
laugh	smooth		iless	sichin	
issue	scream		mooth	serble	
razor	screen			sabbit	
	forest			rafoon	
	lesson			baream	
	private			desius	
				edoice	
				modolt	

Table A2
Hebrew Stimuli

Five-letter complex words		Six-letter complex words		Five-letter complex nonwords	Six-letter complex nonwords
אבדון	destruction	ביטחון	safety	אגלון	אדיגות
אמנות	art	גמישות	flexibility	בשולה	בוכּכות
חגורה	belt	דלילות	thinness	חמשות	גשילות
חגיגה	party	כפילות	redundancy	גשונה	דשישות
חשבון	arithmetic	סוכריה	candy	בוגלת	זימחון
ידיעה	knowledge	כוננית	shelf	דנשור	חגלנות
ילדות	childhood	זיכרון	memory	דומלן	כוממית
ירושה	inheritance			גשנות	פמיגות
יכולת	abilit y			חרנון	סמלנות
כניסה	entrance			ימידה	
לגימה	sip			ישגות	
לטיפה	caress			ידולה	
מבחנה	test-tube			ישולת	
מדריך	guide			כשידה	
מקלט	shelter			לביגה	
נבחרת	top team			לושבה	
נוסחה	formula			לכיחה	
עניבה	tie			משליק	
עבודה	work			מקלמה	
פציעה	injury			ימידה	
פתרון	solution			מגובק	
פסיקה	ruling			נגמקת	
ספנות	shipping			עגורה	
דרכון	passport			כשלד	
בכורה	precedence				
אפודה	sweater				

Five-letter simple words		Six-letter simple words		Five-letter simple nonwords	Six-letter simple nonwords
אבטיח	watermelon	בולדוג	bulldog	חמילה	בוגמון
אביון	pauper	ביריון	bully	חורגף	בומלנג
בנזין	gasoline	סמרטוט	rag	ידואר	גודינה
גבעול	stem	סטודנט	student	ירעור	גימיון
גלריה	gallery	פלסטיק	plastic	ירדגי	דימגנג
זעטוט	tot	ניילון	nylon	ירבעל	חדמוני
חבצלת	lilly	נודניק	nuisance	כומרה	לימיון
חלמון	egg yolk	מוקיון	clown	כידרת	נושמלי
ירבוע	gerbil	מנגנון	system	למוגה	פומדיה
יהלום	diamond	לוליין	acrobat	למיתן	סגודית
יסעור	petrel	ליגיון	legion	מאולה	ביניון
ישראל	Israel	חנווני	grocer	מדזין	דמולון
כוורת	bee-hive	דוכיפת	hoopoe	פושלץ	
כרטיס	ticket	דיסקית	tag	פולדק	
לולאה	loop	גיהנום	hell	סמורט	
מלאכה	work	בומרנג	boomerang	כומקה	
עכביש	spider	דיונון	squid	אמרשל	
עזאזל	Azazel			אגיזר	
פרעוש	flea			אגומל	
פסנתר	piano			בגליק	
כולרה	cholera			גינרה	
אגרטל	vase			דיומן	
				דימון	
				זרשוב	

(*Appendixes continue*)

Table A3
Arabic Stimuli

Five-letter complex words				Six-letter complex words		Five-letter complex nonwords	Six-letter complex nonwords
مزرعة	farm	مكتبة	library	شمعدان	candelabrum	مدرعة	شكعدان
محراث	plough	صناعة	industry	اسطوره	legend	مكراث	اشحوره
تصعيد	acceleration	مرتبة	position	استمرار	continuance	دناعة	استهران
مجاري	cesspit	مدرسة	school	تعليمي	study	مهاري	اغتران
مقبرة	cemetery	مفتاح	key	امتحان	examination	مخدسة	اكتماح
تعبير	expression	اخرا	execution	اجتماع	meeting	مقطرة	استعراد
معركة	battle	مكسور	broken	استعداد	readiness	ملتاح	ازتبار
موقدة	stove	تنظيم	arrange	اختبار	test	مزكبة	مرافحة
خزان	cupboard	طيارة	plane	مكافحة	resistance	اخباج	تعليفي
مرشده	guide	محرقة	burn			رافنة	
مسطرة	ruler	منتوج	product			موقشة	
ترحيب	greeting	تحصيل	achievement			خزانة	
اخبار	news	مشترك	shared			محشدة	
محلقة	barberry					محبقة	
تفكير	thinking					تنخيب	
متجمد	frozen					احباز	
مفهوم	clear						

Five-letter simple words				Six-letter simple words		Five-letter simple nonwords		Six-letter simple nonwords
عائلة	family	مروحة	fan	سكرتيرر	secretary	بائلة	تفالة	سكرفتير
خنزير	pig	جزدان	wallet	كهرباء	electricity	كنزير	مصطحة	كرسباء
زرافة	giraffe	امعاء	intestine	خياشيم	nostril	كرافة	كرعول	بياريم
كركدن	rhinoceros	صنارة	fishhook	تيلفون	telephone	طنازة	كرنيت	تيلبوع
قنطار	ample			نموذج	sample	هصبور		سموذج
عصفور	bird			زعفران	saffron	كعيسة		زعكراج
كنيسة	church			بهلوان	tumbler	زابية		طهبوان
عامود	pillar			مهرجان	festival	بسلون		مرموان
طاولة	table			ارجوان	purple	كنبار		اركوان
زاوية	angle					بناره		
قنينة	bottle					مزوشة		
تلفاز	television					امعال		
بيارة	orange grove					برماز		
حقيبة	bag					مصبلة		

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