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Orthography and the Hemispheres: Visual and Linguistic Aspects of Letter Processing

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Hebrew and Arabic are Semitic languages with a similar morphological structure and orthographies that differ in visual complexity. Two experiments explored the interaction of the characteristics of orthography and hemispheric abilities on lateralized versions of a letter-matching task (Experiment 1) and a global–local task (Experiment 2). In Experiment 1, native Hebrew readers and native Arabic readers fluent in Hebrew matched letters in the 2 orthographies. The results support the hypothesis that Arabic orthography is more difficult than Hebrew orthography for participants who can read both languages and that this difficulty has its strongest effects in the left visual field. In Experiment 2, native Arabic speakers performed a global–local letter detection task with Arabic letters with 2 types of inconsistent stimuli: different and similar. The results support the hypothesis that the right hemisphere of skilled Arabic readers cannot distinguish between similar Arabic letters, whereas the left hemisphere can.

These experiments explore the effects of the orthographic system of languages on hemispheric functioning in the identification of letters. The majority of information about hemispheric abilities in reading comes from studies of native English-speakers reading English. We suggest that this has resulted in a narrow view of hemispheric abilities. Cross-linguistic studies that include languages from other linguistic families and explorations of participants performing in their second or even third language are necessary to widen this view and to see the limits of hemispheric abilities and flexibility.

Psycholinguistic and neurolinguistic cross-language studies have revealed both universal patterns that are independent of language (e.g., Bentin & Ibrahim, 1996; Eviatar, 1996; Faust, Kravetz, & Babkoff, 1993; Feldman, Frost, & Pnini, 1995; Frost, Forster, & Deutsch, 1997; Katz & Frost, 1992; Koriat & Greenberg, 1996; Perfetti & Zhang, 1991; Poizner, Kaplan, Bellugi, & Padden, 1984; Vaid, 1988) and effects that are specific to the characteristics of the languages studied (e.g., Ben Dror, Frost, & Bentin, 1995; Frost, 1998). Previous research in our laboratory has shown that several structural characteristics of languages are related to performance asymmetries in lateralized tasks. Attentional habits related to reading scanning direction can affect the ability of participants to ignore letter stimuli on the side where reading usually begins (Eviatar, 1995) and even performance asymmetries that have been interpreted as reflecting right hemisphere dominance in a nonlanguage task (Eviatar, 1997). In addition, the morphology and orthography of a particular language are reflected in different patterns of indexes of hemispheric processing (Eviatar, 1999). The experiments presented below focus on the effects of orthographic characteristics and grapheme–phoneme relations on lateralized letter identification. We compare performance using Hebrew versus Arabic scripts, because these are similar to and different from each other in interesting ways.

In Hebrew and Arabic, which are Semitic languages, all verbs and most nouns are written primarily as consonantal roots that are differently affixed and vowelized to form the words of the lexicon (Berman, 1978). Most written materials do not include vowels, although there are four letters in each language that, in addition to their role in signifying specific consonants, also specify long vowels. 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. In their unpointed form, the Hebrew and Arabic orthographies contain a limited amount of vowel information and include a large number of homographs. Both languages are written from right to left.

Arabic differs from Hebrew in interesting ways. Arabic has two forms: Literary Arabic (also known as Modern Standard Arabic) is universally used in the Arab world for formal communication and writing. Spoken Arabic is a local dialect that has no written form. The two forms of Arabic are similar in many ways, but they are also sufficiently different to be considered more like two related languages rather than two dialects of the same language (Ibrahim, 1998). Previous research on reading acquisition in Arabic has revealed that this process is slower than in Hebrew (Azzam, 1989; Azzam, 1993; Ibrahim & Eviatar, 2003). In skilled readers, it has been found that reaction times for visual recognition of Arabic words by Arabic speakers are longer than reaction times for Hebrew words by Hebrew speakers (Bentin & Ibrahim, 1996), English words by English speakers, and Serbo-Croatian words by

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Serbo-Croatian speakers (Frost, Katz, & Bentin, 1987). When visual Arabic-word recognition was compared with visual Hebrew-word recognition in native Arabic speakers, Arabic words took longer to be recognized, although the Arabic words were recognized faster than the Hebrew words when the words were presented in the auditory modality (Ibrahim, 1998). We have shown that young Arab children who have been exposed to Literary Arabic function as bilinguals on tests of metalinguistic awareness (Eviatar & Ibrahim, 2000) but that this metalinguistic advantage does not carry over to advantages in the acquisition of reading (Ibrahim & Eviatar, 2003). Although their scores on tests of phonological awareness are higher than those of monolingual Hebrew speakers, their scores on tests of reading achievement are lower. We suggested that this is due to the complexity of Arabic orthography as compared with Hebrew orthography.

This added complexity is found in several characteristics that occur in both orthographies, but to a much larger extent in Arabic than in Hebrew. The first characteristic has to do with diacritics and dots. In Hebrew, dots occur only as diacritics to mark vowels and as a stress-marking device (dagesh). In the case of three letters, this stress-marking device (which does not appear in unvowelized scripts) changes the phonemic representation of the letters from fricatives (*v*, *x*, *f*) to stops (*b*, *k*, *p* for the letters ב, כ, and פּ, respectively). Addition of the stress-marking dot does not change the identity of the letter—it is the same letter, with a different phonemic representation (e.g., ב and בּ are the same letter with two phonemic representations). In the unvowelized form of the script, these letters can be disambiguated by their place in the word, because only word or syllable initial placement indicates the stop consonant. In Arabic, dots are not diacritics, but they are an integral part of the grapheme, where many different letters have a similar, or even identical, base structure and are distinguished only on the basis of the existence, location, and number of dots (for example, the phonemes *t*, *b*, and *n* are, respectively, represented by the letters ب, ت, and ت, and the phonemes *r* and *z* by ر and ز).

The second characteristic of the two orthographies is that some letters are represented by different shapes, depending on their placement in the word. Again, this is much less extensive in Hebrew than in Arabic. In Hebrew, there are five letters that change shape when they are word final: (פּ-ף, צ-ץ, נ-ן, מ-ם, כ-ך). In Arabic, 22 of the 28 letters in the alphabet have four shapes each (word initial; medial; final; and when they follow a nonconnecting letter—for example, the phoneme /h/ is represented by the graphemes ـه and ه in word final position, after a connecting and a disconnecting letter, respectively; ـهـ when it is in the middle of the word; and هـ when it is word initial). The six remaining letters have two shapes each, final and separate.

Thus, the grapheme–phoneme relations are quite complex in Arabic, with similar graphemes representing quite different phonemes, and different graphemes representing the same phoneme. Ibrahim, Eviatar, and Aharon-Perez (2002) have shown that adolescent, native Arabic speakers process visually presented Hebrew letters faster and more accurately than visually presented Arabic letters.

How may these differences affect hemispheric functioning in reading Arabic? The two experiments reported here explored the effects of Arabic orthography on the very early stages of letter identification and grapheme–phoneme conversion. Experiment 1 used a lateralized letter-matching task that has been used extensively in the exploration of hemispheric abilities (e.g., Eviatar & Zaidel, 1992). Experiment 2 used hierarchical letter stimuli (Navon, 1977) in Arabic to look at hemispheric sensitivities to the global and local aspects of these stimuli.

Experiment 1: Letter Matching

To explore the effects of orthography on hemispheric ability in letter identification we used a bilingual, lateralized letter-matching task requiring a physical identity decision. Participants were shown two letters within a visual field and were asked to decide if the two letters were physically identical or not. This type of task has been extensively used in English and has been shown to be within the capabilities of both hemispheres in normal (e.g., Eviatar & Zaidel, 1992) and in commissurotomised participants (Eviatar & Zaidel, 1994). It is therefore a fitting paradigm to test the effects of orthography and language on hemispheric functioning.

Eviatar, Zaidel, and Wickens (1994) reported that normal participants show a type of Stroop effect in this task, where pairs such as *Aa*, to which the correct response is "different," result in longer response times than when the pair is comprised of nominally different letters, such as *AG*. They suggested that this interference results from the automatic processing of letter names even when the task requires a physical identity criterion. As mentioned above, Arabic, and to a lesser extent, Hebrew, contains letters that have different shapes depending on where they occur in the word. In addition, both Hebrew and Arabic have a printed form and a cursive form. This allowed us to create letter pairs in which we manipulated three dimensions:

Shape: The pair of letters could have an identical, different, or similar shape. Our definition of similar shape was pairs of letters that differed by only one feature. In Arabic, this feature was always placement and number of dots, whereas in Hebrew, this feature was always a linear segment in various orientations.

Script: The pair of letters could be in the same or different script (print or cursive).

Name: The pair of letters could represent the same or a different phoneme–grapheme unit.

The five types of letter pairs are presented in Table 1.

These stimuli allow us to explore the different types of complexity in the two orthographies. As shown in Table 1, there are two types of *different* pairs that could result in a Stroop effect similar to *Aa* type pairs in English. These are initial–final pairs, which consist of the word-initial and word-final versions of the same letter, and print–cursive pairs. Both of these conditions contain pairs that are different graphically but represent the same phoneme. Thus, errors or slow responses on these types of pairs are a Stroop effect resulting from the "meaning" of the grapheme. This is in contrast to the *similar* condition, where we have very similar graphic forms, which nevertheless represent completely different phonemes. Errors and slow responses in this condition must be due to difficulty in visual discrimination.

Experiment 1 explored two questions. First, are Arabic letters harder to discriminate than Hebrew letters? This was tested by

Table 1
Examples of Stimuli in the Letter Matching Experiment

Pair type	Hebrew	Arabic	Grapheme relations
Same	א א	ف ف	Identical letters: either both in print or both in cursive
Different			
Print–cursive	א א		The same letter in script and cursive
Different	א ג	ي ب	Letters that differ in more than one feature
Initial–final	מ ם	ﻛ ك	Word initial and final forms of the same letter
Similar	ה ח	ت ب	Letters that differ in only one feature

Note. There are four types of different letter pairs: print–cursive pairs are the same letter represented in print and in cursive; different pairs are different letters that differ in more than one feature; initial–final pairs are the same letter in word initial and word final forms; and similar pairs are different letters that differ in only one feature, a dot in Arabic and a line segment in Hebrew.

looking at the responses of Arabic speakers and Hebrew speakers to both Arabic and Hebrew versions of the test in central vision. The Arabic speakers are bilingual and can read both orthographies, whereas the Hebrew speakers can read only Hebrew. Thus, they are doing the test in Arabic purely as a visual task. The pattern of their responses is an index of the visual complexity of the Arabic orthography, whereas the pattern of the responses of the Arabic speakers is an index of both the visual and the graphemic aspects of this orthography.

Second, how are the two orthographies processed by the hemispheres? By using a physical-identity criterion and both orthographies for both language groups, we will be able to see whether the purely visual aspects of the orthography are the source of the response patterns or whether knowing how to read the orthography is a factor. Pairs of letters will be presented tachistoscopically in a divided visual-field paradigm, such that pairs appearing to the left of fixation are presented initially to the right hemisphere and pairs presented initially to the right of fixation are presented initially to the left hemisphere. Performance asymmetries and interactions are interpreted as reflections of hemispheric processes.

Method

Participants

All participants were undergraduates at the University of Haifa (Haifa, Israel). Twenty native Arabic speakers and 18 native Hebrew speakers participated in the experiment for course credit or 15 NIS (approximately $5.00). All participants were right-handed and neurologically normal. The Arabic speakers were highly fluent bilinguals. All the Arabic speakers had matriculated from high school in Arabic and had passed the entrance examination to the university in Hebrew. The language of instruction at the university is Hebrew. Arab schools begin teaching Hebrew in second grade. None of the Hebrew speakers spoke or read Arabic.

Stimuli and Procedure

Eighty letter pairs were created in each language. Of these, half were identical, and half consisted of two differently shaped letters. The three dimensions of shape, script, and name resulted in four types of *different* stimuli, as presented in Table 1. There were 10 pairs of each type of *different* pairs, resulting in 40 pairs for which the correct response was "different." The letters were presented as black letters on a white background. The Arabic letters appeared in Traditional Arabic font and the Hebrew in David font. Each letter was 1×1 cm in size. The letter pairs were presented in three visual presentation conditions: in the center of the computer screen (central visual field [CVF]), two degrees of visual angle to the left of fixation (left visual field [LVF]), or two degrees of visual angle to the right of fixation (right visual field [RVF]). In the two peripheral conditions, a plus sign appeared in the center of the screen as a fixation point. Stimuli were randomly picked for each participant from the five pair categories: 40 identical stimuli and 10 from each *different* category, resulting in different combinations of letter pairs for different participants. All 80 pairs were presented in random order in the three visual presentation conditions, resulting in 240 trials in the experiment. The participants were asked to press a key marked *same* if the two stimuli had an identical shape, and a key marked *different* if they were not physically identical. Response time and accuracy were measured. All of the participants completed the experiment in both languages. Order of language was counterbalanced within native language groups, such that half of each group completed the Arabic test first and half completed the Hebrew test first.

Participants were tested individually. They were seated with their head on a chin-and-forehead rest that held their eyes 57 cm from the screen. On each trial, the sequence of the events was as follows: A tone of 1000 Hz was presented for 100 ms; the fixation cross appeared for 100 ms; the letters appeared on or around the fixation cross for 100 ms; the mask appeared instead of the letters for 150 ms; and the screen was blank until the participant responded or 3 s had elapsed. After 2 s the next trial began.

Results

The mean median reaction times (RTs) and percent errors for each stimulus type in each visual presentation condition were the dependent variables. The results pertaining to each of the issues raised in the introduction are presented separately.

Are Arabic Letters Harder to Discriminate Than Hebrew Letters?

The responses to stimuli presented in the CVF were analyzed using native language, test language, and shape as independent variables. Three different analyses were performed that differed in the use of the shape variable. In the first analysis, the shape variable had two levels, *same* and *different.* In the second analysis, only *different* responses were used, and the shape variable had four levels, corresponding to the types of pairs presented in Table 1. A third analysis explored the interference effects resulting from the different types of letter pairs.

Same/different decisions. The analysis used a $2 \times 2 \times 2$ mixed analysis of variance (ANOVA), with native language as a between-groups factor and test language and shape (*same* vs. *different*) as within-groups factors. The analysis of median RTs revealed two significant effects: a two-way interaction between native language and test language, $F(1, 36) = 5.06$, $p < .05$, and a main effect of test language, $F(1, 36) = 3.84$, $p = .058$ (Arabic test = 691 ms vs. Hebrew test = 663 ms). The analysis of percent errors revealed a trend toward the same two-way interaction between native and test language, $F(1, 36) = 3.10$, $p = .087$; a main effect of test language, $F(1, 36) = 16.66$, $p < .0005$ (Arabic test = 9.18% vs. Hebrew test = 4.74%); and a main effect of shape, $F(1, 36) = 14.05$, $p < .0005$ (*same* = 9.84% vs. *different* = 4.08%). The mean median RTs and percent errors are listed in Table 2. It can be seen that Arabic speakers respond

Table 2
Mean Median Response Times (RT, in Milliseconds) and Percent Errors to Same and Different Arabic and Hebrew Letter Pairs

	Arabic letters		Hebrew letters	
Participants	RT	% error	RT	% error
Arabic speakers	673 (150)	7.62 (9.3)	676 (172)	5 (8.8)
Hebrew speakers	710 (115)	10.9 (10.2)	649 (88)	4.4 (6.0)

Note. Standard deviations are in parentheses.

at the same speed to stimuli in the two languages, but, like the Hebrew speakers, they make more errors on Arabic letters than on Hebrew letters. Thus, on the whole, the findings suggest that Arabic letters are harder to discriminate than Hebrew letters, irrespective of whether the participant can read the orthography.

Different responses. The second analysis was done on the *different* responses, with the shape variable now designating the different types of pairs, as detailed in Table 1. The ANOVA revealed a three-way interaction between native language, test language and shape for errors, $F(3, 108) = 7.22$, $p < .005$, but not for response times, $p > .12$. This interaction can be seen in Table 3. It can be seen that both groups make more errors on the Arabic than on the Hebrew letters, and on the Hebrew test the two groups make the same amount of errors, whereas on the Arabic test, although both groups make the most errors on *similar* pairs (8.5% for Arabic speakers and 17.8% for Hebrew speakers), this is the only condition where knowing how to read the language has an effect. The simple main effect of native language for these stimuli is significant, $F(1, 36) = 4.47$, $p < .05$, whereas it is not significant for the other types of pairs.

Interference effects. To explore the effects of the pair types, we computed three interference scores in the following manner: (a) To test for the hypothesized Stroop-like effects of script, we computed the difference between the print–cursive pairs and the *different* pairs; (b) to test for the hypothesized Stroop-like effects of form, we computed the difference between the initial–final pairs (in which the same phoneme is represented by an initial and final version of the grapheme) and the *different* condition; and (c) to test for the effect of visual complexity, we computed the difference between the *similar* condition (in which pairs representing different phonemes differed by only one feature) and the *different* condition.

These data were analyzed using a three-way mixed ANOVA with native language as a between-groups factor, and test language and interference (script, form, and visual complexity) as within-subject factors. The analysis revealed a significant three-way interaction in errors, $F(2, 72) = 6.13$, $p < .005$, but not in RT. The cell means are listed in Table 4. It can be seen that both groups experience the most interference from visual complexity and that the interaction in errors results from this effect being the strongest for Hebrew speakers in Arabic.

Planned comparisons looked at the effects of native and test languages in each type of interference measure. These revealed no significant effects due to form interference in either RT or errors. Script interference revealed an interaction of native and test languages in errors, $F(1, 36) = 6.24$, $p < .05$, but not in RT. Hebrew speakers made more errors in Arabic here, because they cannot read Arabic, and the cursive and print forms of the graphemes were difficult for them to distinguish. Thus, there were no effects that could be due to Stroop-like interference. Interference due to visual complexity revealed a simple main effect of test language in RT, $F(1, 36) = 25.24$, $p < .0001$, and in errors, $F(1, 36) = 22.27$, $p < .0005$, with visual complexity having the largest effect in the Arabic test. This resulted in a significant interaction of native and test language in errors, $F(1, 36) = 12.39$, $p < .005$, and approached significance in RT, $F(1, 36) = 3.16$, $p = .08$. That is, as reported above, although Arabic speakers made fewer errors than Hebrew speakers in the *similar* condition in Arabic, they still made significantly more errors and responded more slowly to this condition than to the other pair types. On the Hebrew test, visual complexity had no effect on errors and a marginal effect on RT.

Discussion of Central Presentations

The results presented so far are pertinent to the question of the relative discriminability of the Hebrew and Arabic orthographies. We see that both Arabic speakers and Hebrew speakers make more

Table 3
Mean Percent Errors to the Four Types of Different Pairs

	Arabic letters		Hebrew letters	
Pair type	Arabic speakers	Hebrew speakers	Arabic speakers	Hebrew speakers
Different	2.5 (7.2)	0.5 (2.4)	1 (3.1)	2.2 (5.5)
Initial–final	2.5 (5.5)	1.6 (5.1)	2.5 (5.5)	3.3 (5.9)
Print–cursive	6.5 (9.3)	9.4 (11.1)	2 (6.2)	0 (0)
Similar	8.5 (11.8)	17.8 (15.2)	4 (6.8)	1.1 (3.2)

Note. Standard deviations are in parentheses.

Table 4
Stroop-Like Interference Effects in Response Times (RT, in Milliseconds) and Percent Errors

	Arabic letters				Hebrew letters			
	Arabic speakers		Hebrew speakers		Arabic speakers		Hebrew speakers	
Interference	RT	% error	RT	% error	RT	% error	RT	% error
Form	9.15 (58)	0 (4.6)	−9.67 (85)	1.11 (3.23)	4.75 (84)	1.5 (5.87)	−12.11 (66)	1.11 (7.58)
Script	10.92 (51)	4.0 (10.5)	10.13 (64)	8.89 (10.79)	−9.15 (68)	1.0 (7.18)	−16.64 (46)	−2.22 (5.48)
Visual complexity	**84.28 (93)**	**6.0 (8.21)**	**138.58 (87)**	**17.22 (14.87)**	**28.75 (48)**	3.0 (7.3)	23.78 (52)	−1.11 (6.76)

Note. Form interference = the difference between *different* pairs and initial–final pairs; Script interference = RT difference between *different* and script pairs; Visual complexity interference = the difference between *different* pairs and *similar* pairs. Interference effects that are significantly different from 0 ($p < .05$) are marked in bold. Standard deviations are in parentheses.

errors in Arabic than in Hebrew. These findings converge with those reported by Ibrahim et al. (2002) that healthy, Arabic-speaking adolescents processed Hebrew letters faster than Arabic letters.

The findings also support the hypothesis that letters differing by a single visual feature (the *similar* condition) are harder to distinguish from each other in Arabic than in Hebrew. The feature that differed between letters in Arabic was always the location and number of dots around an identical basic shape, whereas the feature that differed between letters in Hebrew was always a line segment. Recall that the prediction was that for pairs in the print–cursive and initial–final conditions, knowing how to read the orthography should hinder responses, because although the physical shape of the letters is different, they represent the same phoneme. The letter pairs in the *different* and *similar* conditions always represented different phonemes, such that knowing how to read the orthography should facilitate responses. The results shown in Tables 3–4 support only the latter part of this hypothesis: On the Hebrew test, which both groups of participants know how to read, there were no interference effects and only marginal effects of visual complexity. On the Arabic test, there were no Stroop-like interference effects from different graphemes that represent the same phoneme; however, we see that although visual complexity resulted in both groups of participants making more errors on *similar* pairs, this effect is mitigated by knowing how to read the orthography, because Arabic speakers made fewer errors than Hebrew speakers. The conclusion from these results is that the Arabic orthography is more visually complex than the Hebrew orthography, such that literate Arabic speakers find it more difficult to discriminate Arabic letters than they do Hebrew letters.

How Are the Two Orthographies Processed by the Hemispheres?

The responses to the peripheral conditions were analyzed in the same manner as those in the central presentation condition, with the addition of visual field (LVF vs. RVF) as a within-subject variable in the ANOVA.

Same/different decisions. The analyses of *same–different* decisions revealed a significant three-way interaction between native language, test language, and visual field in RT, $F(1, 36) = 6.51$, $p < .05$, and in errors, $F(1, 36) = 6.30$, $p < .05$. These effects are illustrated in Figure 1. It can be seen that for RT (top panel), the interaction is due to the finding that for all of the conditions except one, there is a significant simple main effect of visual field (a right visual field advantage [RVFA]). The only condition that does not exhibit this effect is the one where Hebrew speakers performed the task in Arabic, which is also the only condition in which the participants could not read the language. For errors (bottom panel), the interaction is due to the finding that only one

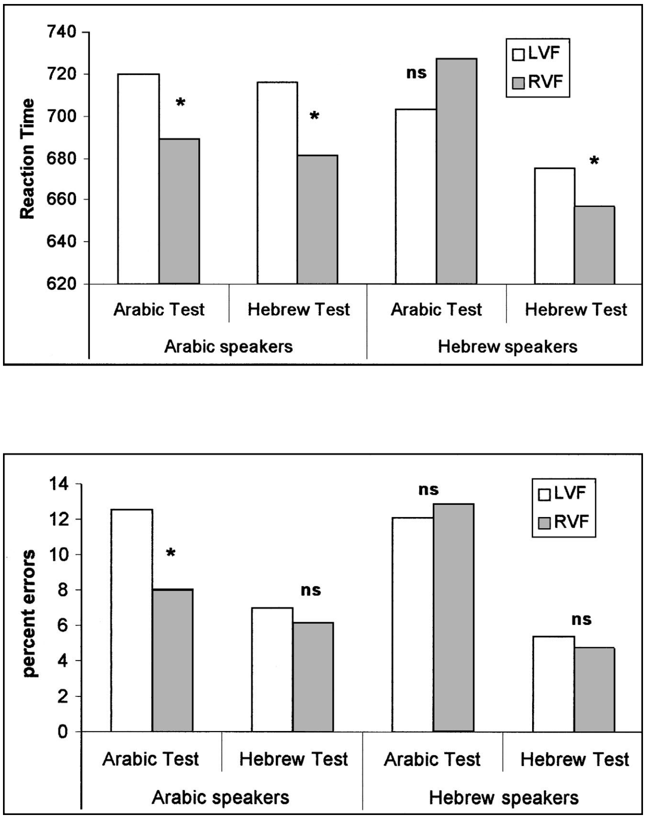

Figure 1. Three-way interaction in both reaction times (in milliseconds; top panel) and errors (bottom panel) between native language, test language, and visual field. In reaction times, all conditions in which the participants can read the language of the test result in a right visual field advantage (RVFA), indicating left hemisphere specialization for the task. In errors, only Arabic speakers in Arabic reveal a significant RVFA, with very high error rates in the left visual field (LVF) and very low error rates in the right visual field (RVF). *$p < .05$.

condition, that of Arabic speakers doing the task in Arabic, resulted in a significant simple main effect of visual field (an RVFA). It can be seen that these participants made as many errors in the LVF as did the Hebrew speakers (who cannot read Arabic) in both visual fields. Planned comparisons reveal that the responses of the Arabic and Hebrew speakers do not differ in the two visual fields when the task was in Hebrew. When the task was in Arabic, the two groups responded differently in the RVF, $F(1, 36) = 7.04$, $p < .05$, but not in the LVF, $p > .7$. That is, knowing how to read Arabic facilitated responses in the RVF but not in the LVF.

Different responses. Analyses of *different* responses revealed a significant four-way interaction in RT, $F(3, 108) = 2.84$, $p < .05$, but not in errors, $p > .8$. The mean median RTs are listed in Table 5. Planned comparisons revealed that the three-way interaction between native language, test language, and visual field is significant only in the *similar* condition, $F(1, 36) = 13.47$, $p < .0001$. As can be seen in Table 5, all the other pair types resulted in similar response times in the two groups of participants, irrespective of the language of the test.

Further comparisons within the *similar* condition revealed that the test language by visual field interaction is significant or marginally significant, for both groups: for Arabic speakers, $F(1, 19) = 6.10$, $p < .05$; for Hebrew speakers, $F(1, 17) = 7.17$, $p < .06$. However, close inspection of the bottom row in Table 5 reveals that these interactions are in opposite directions for the two groups: For Arabic speakers, Arabic *similar* pairs were not harder than Hebrew *similar* pairs in the RVF (749 ms vs. 746 ms); however, in the LVF, Arabic pairs were responded to significantly more slowly than Hebrew pairs (824 ms vs. 751 ms), $F(1, 19) = 14.12$, $p < .005$. For Hebrew speakers, we see the opposite pattern: Responses to letters in the two languages are equivalent in the LVF (Arabic = 875 ms, Hebrew = 800 ms, $p > .18$), whereas in the RVF, these participants respond faster to Hebrew (682 ms) than to Arabic letters (856 ms), $F(1, 17) = 15.04$, $p < .005$.

Interference effects. In order to examine the hypothesized interference effects in the two hemispheres, we computed interference scores as before: a score representing form interference (initial–final − *different*), a score representing script interference (print–cursive − *different*), and a score representing interference due to visual complexity (*similar* − *different*). These data are presented in Table 6. Both RT and error interference were tested. The RT results revealed a trend toward a four-way interaction, $F(2, 72) = 2.69$, $p = .075$, where the three-way interaction between native language, test language, and visual field was significant only in the *similar* condition, $F(1, 36) = 8.05$, $p < .01$, and not for the other types of pairs. It can be seen that Hebrew speakers show a large effect of visual complexity in both visual fields in Arabic and a significant effect of visual complexity only in the LVF in Hebrew. The Arabic speakers show significant effects of visual complexity in both languages in both visual fields.

The three-way interaction between native language, visual field, and interference was significant in RT, $F(2, 72) = 4.76$, $p < .05$, and reflected the same phenomenon, namely, that in the conditions where the participants knew how to read the language (bilinguals in both languages, and Hebrew speakers in Hebrew), all types of interference were always greater in the LVF than in the RVF.

The error data showed a significant interaction between native language, test language, and interference type, $F(2, 27) = 7.34$, $p < .005$, which is the same interaction shown in the CVF data (see Tables 3–4), where Hebrew speakers made many more errors in Arabic in *similar* pairs and in the script interference pairs because these were visually similar as well, whereas the groups did not differ in the error patterns on the Hebrew version of the test.

Discussion of Peripheral Presentations

The second question addressed by this experiment is the functioning of the two cerebral hemispheres in this task in the two languages. This question is answered by the findings shown in Figure 1: For Hebrew speakers, letters in both Arabic and Hebrew are responded to with equivalent accuracy in the two visual fields (and by inference, by the two hemispheres). On the Arabic test, accuracy is low because the task is a difficult visual discrimination task; and on the Hebrew test, accuracy is high because both hemispheres recognize letters (Eviatar & Zaidel, 1992). However, the picture is different when we look at the Arabic speakers. Here we see that both hemispheres achieve equivalent and good accuracy on the Hebrew test but that there is a marked asymmetry in the Arabic test, where the responses in the RVF (left hemisphere [LH]) are equivalent to the responses on the Hebrew test, but the responses in the LVF (right hemisphere [RH]) contain as many errors as the responses of Hebrew speakers on these stimuli—as though the RH of these Arabic speakers cannot read Arabic. This conclusion is somewhat mitigated by the analyses of errors on

Table 5
Mean Median Response Times (in Milliseconds) to the Four Types of Different Pairs in the Two Language Groups in the Hebrew and Arabic Versions of the Test in the Two Peripheral Visual Fields

	Arabic speakers				Hebrew speakers			
	Arabic letters		Hebrew letters		Arabic letters		Hebrew letters	
Pair type	LVF	RVF	LVF	RVF	LVF	RVF	LVF	RVF
Different	699 (134)	664 (123)	680 (132)	670 (146)	675 (104)	671 (90)	662 (90)	663 (103)
Initial–final	723 (153)	695 (126)	721 (141)	693 (145)	658 (90)	691 (125)	669 (86)	663 (77)
Print–cursive	792 (134)	680 (130)	756 (163)	663 (146)	714 (122)	705 (97)	691 (114)	634 (74)
Similar	824 (122)	749 (193)	751 (128)	746 (185)	875 (215)	856 (223)	800 (148)	682 (93)

Note. Standard deviations are in parentheses. LVF = left visual field; RVF = right visual field.

Table 6
Stroop-Like Interference Effects in Response Times (RT, in Milliseconds) and Percent Errors

	Arabic speakers				Hebrew speakers			
	Arabic letters		Hebrew letters		Arabic letters		Hebrew letters	
Interference	LVF	RVF	LVF	RVF	LVF	RVF	LVF	RVF
Form								
RT	24 (101)	**32 (50)**	41 (139)	23 (58)	−17 (76)	−19 (62)	6 (72)	0 (67)
% error	3.5 (8.8)	−0.5 (6.0)	1.5 (5.87)	1.0 (7.2)	−0.6 (4.2)	−1.7 (3.4)	−1.1 (4.7)	−1.7 (3.8)
Script								
RT	**93 (139)**	16 (43)	**76 (117)**	−8 (52)	39 (8.2)	**34 (45)**	28 (83)	−30 (61)
% error	**5.5 (9.9)**	**5.0 (8.3)**	−0.5 (6.0)	2.0 (4.1)	**11.1 (11.3)**	**8.3 (15.8)**	2.2 (6.5)	−1.7 (3.8)
VC								
RT	**126 (87)**	**85 (116)**	**71 (78)**	**76 (89)**	**199 (201)**	**185 (172)**	**138 (125)**	19 (40)
% error	**8.0 (8.9)**	**4.0 (6.8)**	2.5 (7.2)	**4.0 (8.2)**	**18.9 (16.7)**	**15.0 (19.2)**	1.1 (5.8)	0.0 (4.9)

Note. Form interference = the difference between *different* pairs and initial–final pairs; Script interference = RT difference between *different* and script pairs; Visual complexity (VC) = the difference between *different* pairs and *similar* pairs. Interference effects that are significantly different from 0 ($p <$ .05) are in bold. Standard deviations are in parentheses. LVF = left visual field; RVF = right visual field.

different pairs, which revealed that these are distributed differently in the two groups, showing that the RH of Arabic speakers was not only susceptible to Stroop effects from initial and final letter forms (see Table 6) but also made fewer errors in the visual complexity condition, suggesting that orthographic knowledge is affecting responses to stimuli in the LVF after all. However, it is still the case that the Arabic speakers revealed much higher levels of performance differences between the two visual fields in Arabic than in Hebrew and that these asymmetries were due to slower and less accurate responses to Arabic stimuli in the LVF.

The results of this experiment support the hypothesis that the visual characteristics of an orthography interact with hemispheric abilities to determine performance asymmetries in lateralized tasks. Some performance patterns are general: In both languages we see that letter pairs that differed by only one feature (the location of a dot in Arabic and of a line segment in Hebrew) were more difficult to tell apart when they were presented to the LVF than to the RVF. This is presumably a reflection of the greater sensitivity of the LH than of the RH to local elements of visual displays (e.g., Robertson, 1995). In addition, this pattern is seen most clearly for each group in their native language, suggesting that amount of experience with the orthography may be important. The effects of experience and of orthographic knowledge were apparent in the differences between the two groups doing the task in Arabic, where only one group possessed this knowledge and the other was performing the task purely on the basis of shape. The specific interactions of Arabic orthography with hemispheric ability were apparent in the responses of the Arabic–Hebrew bilingual participants, who show the effect in Arabic but not in Hebrew.

We claim that this occurs because Arabic letters are very difficult to distinguish, with many very similarly shaped letters representing different phonemes and many differently shaped letters representing the same phoneme. Specifically, very-similar different letters are often only distinguished by the location and number of small elements in the letter, such as dots. This is important, because there is much research suggesting that there is differential hemispheric sensitivity to the global and local aspects of visually complex stimuli (for a review, see Robertson & Lamb, 1991). Thus, we are making a very specific claim: that the RH does not contribute to reading in Arabic as it does to reading in Hebrew or in English and that this is because it cannot distinguish between very similar letters that represent different phonemes. To test this claim directly, we performed Experiment 2.

Experiment 2: Global–Local Task in Arabic

The global–local paradigm (Navon, 1977) has been extensively used in the study of the microgenesis of object perception. In a typical experiment, participants are presented with stimuli in which local elements are aligned to form a global configuration, where the local and global aspects of the stimulus are either congruent (e.g., a large *H* made out of small *H*s) or incongruent (e.g., a large *H* made out of small *S*s) and what is measured is the relative speed of processing and interference effects when attention is directed to one level or another (for a review, see Kimchi, 1992). A general finding has been that information from the global level of the stimulus is processed faster and is harder to ignore than information from the local level of the stimulus (Navon, 1991). This is seen in identification tasks, where responses to global letters are faster than responses to local letters, and in the incongruent conditions, where interference from the global level on responses to stimuli on the local level is larger than interference of the local level on responses to the global level. Use of lateralized versions of the paradigm with both healthy participants (e.g., Huebner, 1998; Sergent, 1982) and unilaterally brain-damaged patients (Lamb, Robertson, & Knight, 1990) has suggested that the RH is more sensitive to the global aspects of hierarchically structured stimuli than is the LH and that the LH is more sensitive to the local, or element, level of these stimuli than is the RH. In general, the finding has been that interference from the global level on responses to stimuli on the local level is larger in the LVF than in the RVF, whereas interference from the local level on responses to the global level is larger in the RVF than in the LVF.

To examine our hypothesis that the RH cannot differentiate between very-similar different letters in Arabic, whereas the LH can do so, we created a global–local task with two types of incongruent stimuli: one where the two letters on the two levels of the hierarchical stimulus were physically very different from each other, namely, ت and م; and another where the two letters were very similar to each other, namely, ت and ب. In both conditions we compared responses to these incongruent stimuli to responses to congruent stimuli. Our hypothesis predicts that the incongruent stimuli created from very similar letters will be processed as congruent stimuli in the LVF but as incongruent stimuli in the RVF. In other words, the LH will differentiate between ت and ب but the RH will not.

Method

Participants

The participants were 12 undergraduate students (6 males) at the University of Haifa (Haifa, Israel). All participants were right-handed, neurologically normal, and native speakers of Arabic. All participants were trilingual, having started studying Hebrew in second grade and English in third grade.

Stimuli

The experiment was divided into four blocks of 36 trials each. In two of the blocks, the task of the participants was to determine if the target presented was ت or م. This was called the *different* condition, because the two letters are physically very different. In the other two blocks, the task was to determine if the target was ت or ب. This was called the *similar* condition, because the two letters are physically very similar. Within each of these conditions, the target was on the global level in one block and on the local level in the other. The order of the four blocks was counterbalanced over the participants.

Seven hierarchical stimuli were constructed, using the Arabic letters م, ت, and ب. These represent the phonemes /m/, /t/, and /b/, respectively. For each letter, a "consistent" version was created, which comprises the global shape made of the local shape, both depicting the same letter. In addition, four "inconsistent" stimuli were created: for the *different* condition, a global (large) letter ت made of the local (small) letter م, and a global (large) letter م made of the local (small) letter ت; for the *similar* condition, a global (large) letter ت made of the local (small) letter ب, and a global (large) letter ب made of the local (small) letter ت. These are illustrated in Figure 2.

Each local stimulus letter subtended 0.5 × 0.5 degree of visual angle. Each global stimulus letter subtended 4 × 4 degrees of visual angle. The stimuli were presented laterally such that the center of the global stimulus was 3.5 degrees offset from the fixation point in the center of the screen.

Procedure

The participants were seated with their chin in a chin rest that held their eyes at a distance of 57 cm from the center of the screen. The order of events for each trial was as follows: The central fixation point appeared for

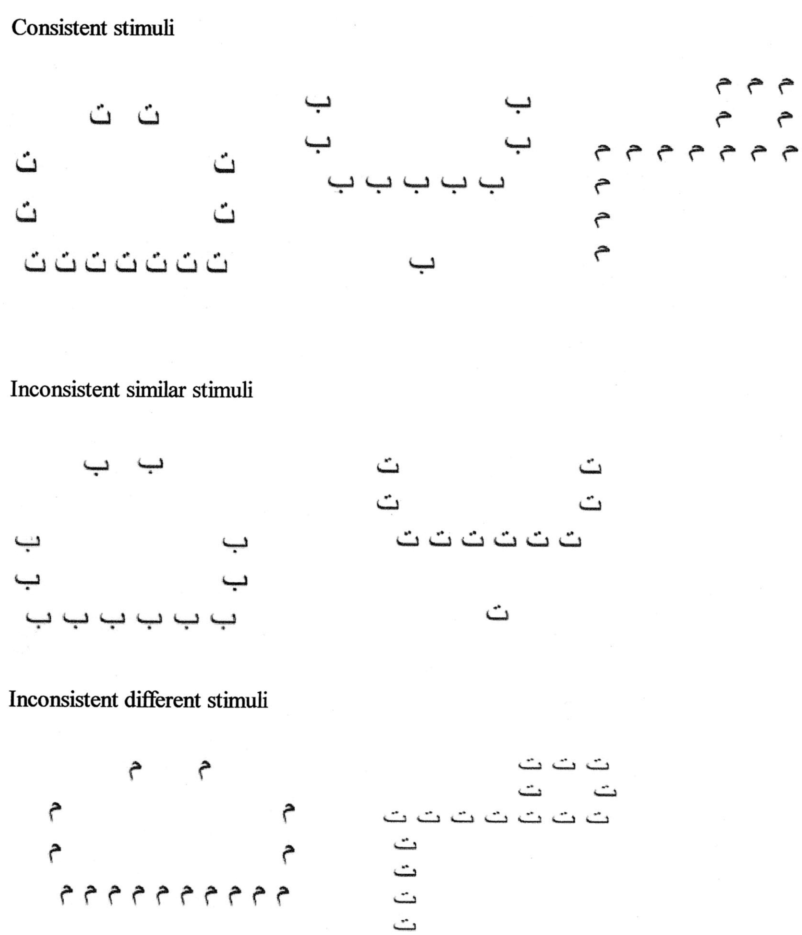

Figure 2. Stimuli used in Experiment 2.

100 ms alone, and then the stimulus appeared either to the right or to the left for 100 ms. The stimulus was replaced by a mask consisting of a 4 × 4 degrees square of random dots with an 8:1 white-to-black ratio, such that approximately 89% of the mask was white. The mask was presented until the participant responded or until 3 s had elapsed, and, after a 2-s interval, the next trial began.

To facilitate the transition between blocks (stimuli set and task), each one was preceded by 12 practice trials with feedback. At the beginning of the experiment, a brief explanation of the tasks was given by the experimenter and a sample of the stimuli was presented. Participants were told that maintaining fixation was extremely important and that it increases accuracy. Responses were made by pressing either the upward arrow key (labeled ت) on the computer keyboard or the downward arrow key (labeled ب, م) with the right hand's first or middle finger.

Results

Correlations between RTs and error scores revealed no speed–accuracy trade-offs. In the blocks using *different* incongruent stimuli, participants made 6% errors, whereas the *similar* incongruent blocks resulted in 8% errors. Given the paucity of errors and the fact that the hypotheses are about RT, only analyses of median RTs are reported.

We analyzed the Task × Congruency × Visual Field effects separately for the *different* incongruent and the *similar* incongruent conditions. Analysis of the *different* incongruent condition revealed the effects illustrated in the upper panels of Figure 3. It can be seen that the major findings reported in previous studies have been replicated: Responses to the global task (499 ms) are faster than responses to the local task (584 ms), $F(1, 11) = 8.59$, $p < .05$. In addition, responses to congruent stimuli (516 ms) are faster than responses to incongruent stimuli (567 ms), $F(1, 11) = 12.24$, $p < .005$. The Task × Visual Field interaction is significant, $F(1, 11) = 5.33$, $p < .05$, with faster responses in the LVF (487 ms) than in the RVF (511 ms) in the global task, and the opposite pattern (LVF = 595 ms, RVF = 572 ms) in the local task. It can also be seen that the interference patterns are different in the two visual fields: with greater interference (the RT difference between congruent and incongruent stimuli) from the global level in the LVF (50 ms) than in the RVF (37 ms), and greater interference from the local level in the RVF (66 ms) than in the LVF (51 ms).

The analysis for the blocks in which the incongruent letters were created from similar letters are shown in the lower panels on Figure 3. It can be seen that the global advantage occurs here as well, with responses on the global task (455 ms) being faster than on the local task (584 ms), $F(1, 11) = 21.32$, $p < .05$. There is a significant interaction between task and congruency, $F(1, 11) = 16.71$, $p < .005$, because there is no effect of congruency in the global task (e.g., there is no interference from the local level on global decisions), but there is an interference effect in the local task (e.g., interference from the global onto the local level). Most important, the three-way interaction between task, congruency, and visual field is significant, $F(1, 11) = 13.93$, $p < .005$. As

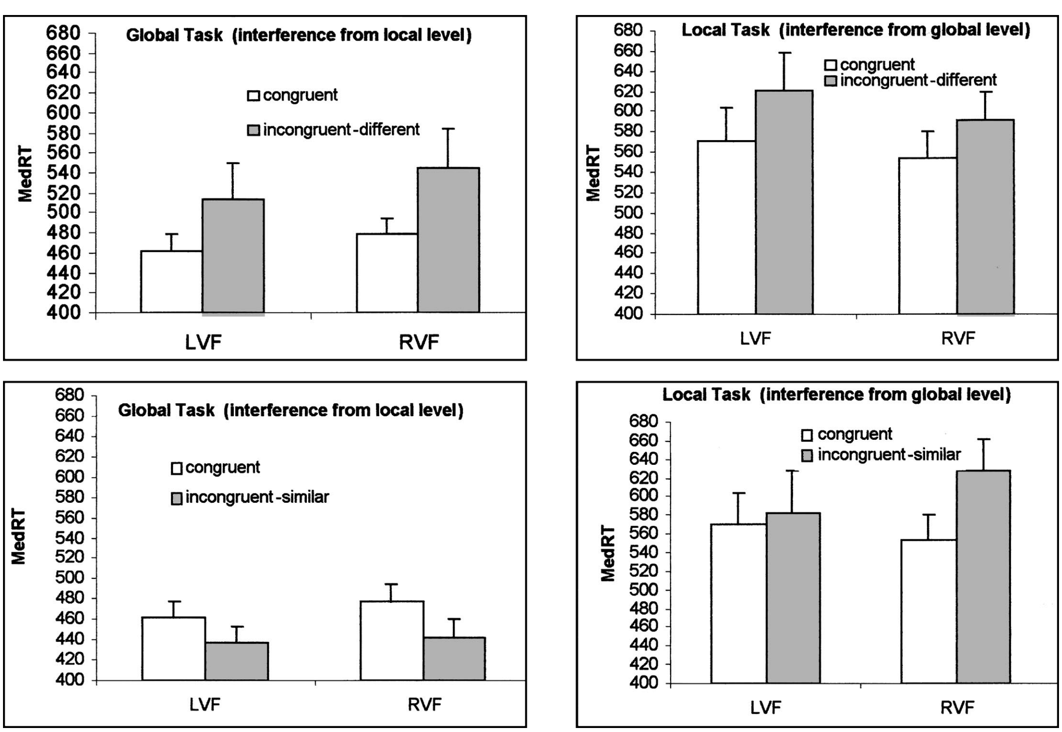

Figure 3. Response times to congruent and incongruent hierarchically structured letters. Top panels show median response times (med RT; in milliseconds) for incongruent stimuli that were created from letters that differ in their global configuration (ت and م). Bottom panels show median response times (in milliseconds) for incongruent stimuli that were created from letters that differ only in their local aspects (ت and ب). Error bars represent standard errors. LVF = left visual field; RVF = right visual field.

can be seen in Figure 3, and as supported by planned comparisons, on the global task there was no interference at all from the local level in either visual field. That is, in both visual fields, the differences between these similar letters on the local level had no effect on responses on the global level. However, on the local task, incongruent stimuli presented to the LVF (RH) were processed as if they were congruent—there is no interference at all (12 ms). When these stimuli were presented to the RVF (LH), they did result in significant interference (72 ms), $F(1, 11) = 10.57$, $p < .01$.

Discussion

The results of this experiment clearly reveal the differential effects of orthographic similarity in the two visual fields. In the condition where the incongruent stimuli were created from very different letters, we found interference effects in both directions: from the global level onto decisions on the local level and from the local level onto decisions on the global level. As previously reported, these effects interacted with the visual field of presentation, with larger interference from the global to the local levels in the LVF than in the RVF, and larger interference from the local level to the global level in the RVF than in the LVF. These results converge with many other reports of lateralized versions of this task to suggest that the hemispheres differ in their sensitivity to the global and local aspects of hierarchical stimuli.

When we used very similar-looking letters in the incongruent stimuli, we got a somewhat different pattern: Responses to the global level were faster than responses to the local level, but the interference effects were asymmetrical. There were no interference effects at all from the local level onto decisions on the global level. Interference effects were limited to the condition in which the stimuli were presented to the RVF (directly to the LH) and the decision had to be made on identity of the letters at the local level.

Our results show that when the participants were paying attention to the local level, when the two letters making up the stimulus were very different, interference from the global level occurred in both visual fields. That is, the implication is that both hemispheres were sensitive to the incongruence of the stimulus—both hemispheres reveal effects of the difference in the letters making up the global and local levels of the stimulus. However, when the different letters making up the stimulus were very similar, only responses in the RVF show an effect of the difference in the letters, implying that only the LH was sensitive to the incongruence of the stimulus.

Both hemispheres seemed to process incongruent similar stimuli as congruent, when the "wrong" letter was on the local level. These findings are consistent with the global precedence hypothesis (Navon, 1977, 1991), which posits that the processing of global features is faster and less vulnerable to interference than is the processing of local features.

General Discussion

The results of the present study suggest that one underlying cause of the relative difficulty in acquiring and reading Arabic may be the lower involvement of the RH in this process. In Experiment 1, the finding of a larger difference in performance levels in the two visual fields, suggesting larger differences in abilities between the two hemispheres, was specific to Arabic. The same RH was much more able to distinguish between letters in Hebrew than it was in Arabic. The hypothesis raised to explain this was that the RH is insensitive to the local details of very similar letters (such as the existence or placement of dots around a similar basic shape) in Arabic. The results of Experiment 2 support our interpretation by showing that both hemispheres were insensitive to the local aspects of letters on the local level when attention was directed to the global level of the hierarchical stimulus. However, when attention was directed toward the local level of the hierarchical stimulus, only the LH distinguished between ت and ب on the basis of the placements of dots and evinced interference effects. The RH responded to these incongruous stimuli as if they were constructed from the same letter.

In summary, the results of Experiment 1 show that the hemispheres of bilingual readers respond differently to the orthographies of Arabic and Hebrew. The results of Experiment 2 suggest that this may be because there is an interaction between hemispheric abilities in the processing of local and global aspects of complex visual stimuli and the requirements of the orthography of Arabic.

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