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Research report

Word length effects in Hebrew

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Abstract

Numerous lateralization studies have reported that word length has a stronger effect in the left visual field (LVF) than in the right visual field (RVF) for right-handed people due to hemispheric asymmetry for language processing. Alternatively, early perceptual learning theory argued that the length effects might depend on the frequency of having read words at various lengths displayed at different retinal locations. The two alternatives were tested with right-handers participants who were native speakers of Hebrew which is read from right to left, that is Hebrew readers have a different perceptual experience than English readers. We found the predicted interaction between word length and hemifield; however, longer latencies to longer letter strings were found at both visual fields. We argue that these results are best accounted by the SERIOL model of letter-position encoding [C. Whitney, M. Lavidor, Why word length only matters in the left visual field. Neuropsychologia 42 (2004) 1680–1688].

Theme: Neural basis of behavior
Topic: Cognition

Keywords: Split fovea; Nasotemporal overlap; Visual word recognition; Word length; Perceptual learning; Reading direction

1. Introduction

Visual word recognition in skilled reading varies in a very systematic way with the location of the word in the visual field. It varies with retinal eccentricity, as the acuity of the eye drops of dramatically on either side of the fixation point, even within the fovea [19]. Word recognition has also been reported to vary between the two visual hemifields, with a typical right visual field (RVF) advantage with right-handed subjects [9,11].

When word length (i.e., number of letters) was manipulated in lateralization studies (in English), the RVF advantage increased for longer words, reflecting an interaction between visual hemifield and word length, such that the number of letters in a word has a stronger effect in the left visual field (LVF) than in the RVF [2,5,6,9,10,27]. The length and hemifields interaction was found even when the orthographic neighbourhood size of the different-length words was controlled [12]. However, the reduced effect of length in the RVF only occurred when words were presented in a standard, horizontal format. The presentation of non-words also shows length effects in both hemifields [5,9].

The difference in the way words are perceived in the two hemifields has repeatedly been attributed to cerebral hemispheric differences in processing written language [9]. It is well established that inferior temporal structures of the left hemisphere are systematically activated in word recognition tasks, and lesions in these cortical regions produce a reading deficit that is characterized by a pronounced word length effect [7]. Whether or not variations of word length effects in lateralized displays (with normal readers) are related to processes in these left cortical regions, is yet to be demonstrated. However, there is little doubt that the two hemispheres are differentially involved in reading Roman scripts. As each hemifield projects entirely to the visual cortex of the contralateral hemisphere, visual word recog-

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nition could be more efficient in the right visual field because information is directed initially to the language-dominant left hemisphere [3,4]. One aspect of this efficiency is the smaller (or absent) length effect when words are presented to the RVF. This view is the cerebral asymmetry theory to account for the RVF advantage over the LVF for longer words.

The alternative account for the different length effects in the two visual fields is based on the perceptual learning theory. The possibility of perceptual learning processes that accompany the reading process may offer another explanation for the observed visual field effects in the perception of print. According to Nazir [17], perceptual learning occurs during processing of print; hence, reading practice leads to improvement in performance. This improvement, however, appears to depend on the precise configuration of the stimulus; therefore, participants who learned to recognize an unfamiliar visual pattern displayed at one single location on the retina may be significantly better at recognizing this pattern when displayed at the trained location than when displayed at other locations in the visual field [1,18]. The same preference of the trained location may also be true for reading processes. Nazir [17] argued that the length effects found in the LVF, but not in the RVF, might depend on the frequency of having read printed words of various lengths displayed at different retinal locations. Since the preference to fixate on the first letters (hence the word is presented to the RVF[1]) is not sensitive to word length, word recognition performance is insensitive to word length in the RVF, but performance decreases as word length increases in the LVF.

Thus far we have presented two alternative accounts for the word length and visual fields interaction: cerebral asymmetry versus perceptual learning. Whitney [24] has recently addressed these issues under the SERIOL model of letter position encoding. The SERIOL model is a theoretical framework which specifies how the early, retinotopic representation of a string is transformed into an abstract encoding of letter order [21–23,25]. Aspects of the proposed transformations differ across hemispheres, yielding asymmetric activation patterns. This asymmetry depends on reading direction. Thus the SERIOL model provides a mechanistic account of the effects of perceptual learning in visual word recognition. Such an asymmetry in activation patterns could potentially explain the differing effects of string length.

If activation patterns are the source of the hemifield asymmetry, it should be possible to manipulate the asymmetry of the length effect by adjusting activation patterns, via position-specific changes to contrast levels. Based on precise predictions stemming from the SERIOL model, we performed a contrast manipulation that was expected to abolish the LVF length effect (via facilitation for longer words as compared to the control condition) and to create an RVF length effect (via inhibition for longer words). These predictions were indeed confirmed [26]. These results demonstrate that a length effect is not inherent feature of RH lexical-level processing, for if it were, it would not be possible to eliminate it via a visual manipulation. Therefore, the LVF length effect does not arise from an RH-specific mode of lexical access.

However, these results do not preclude the possibility that hemispheric specialization does play some role in the LVF length effect. For LVF presentation, it would be necessary to transfer the orthographic information from the RH to the language-dominant LH. Such callosal transfer may affect the RH activation pattern, contributing to the LVF length effect. That is, hemispheric specialization may play a role at a sub-lexical level due to the degrading effect of callosal transfer on the activation pattern. Thus, while Whitney and Lavidor (2004) showed that the LVF length effect arises from the activation pattern at the visual/orthographic level, a remaining issue is to determine the respective contributions of reading direction (perceptual learning) and callosal transfer (hemispheric dominance).

One way to tease apart these factors is to compare readers who have similar brain organisation for language but differ in their perceptual experience of reading. If individuals with right-to-left reading experience were to show the same word length and hemifield interaction as participants with left-to-right reading direction (i.e., Roman languages), this would imply that hemispheric dominance is the primary determinant of the length effect. However, the opposite pattern of performance for the Hebrew readers (e.g., word length effects for RVF but not LVF targets) would support the primacy of the perceptual learning account. Of course, a finding a length effect in both visual fields is also a logical possibility, which would indicate that both hemispheric dominance and reading direction are contributing factors.

Deutsch and Rayner [8] have shown that fixations distribution when reading Hebrew words (from right to left) is a mirror image to English. According to the perceptual learning theory, these different landing patterns should have generated a length effect to the right, but not to the left of fixation. We will test this prediction in the current study.

Lavidor, Ellis, Shillcock and Bland [14] have reported word length effects in the left side of centrally presented words (the first letters) but not the right side (the last letters), replicating the well-established finding of word length and hemifield interaction [9]. These results support the theory that the representation of foveal targets is split between the two cerebral hemispheres along the vertical midline [2,3,13,16]. Thus hemifield effects can be investigated within fixated stimuli.

In the current study, we replicate the Lavidor et al. [14] study with native speakers of Hebrew in order to compare

[1] Recently there is a converging evidence that the representation of foveal stimuli (such as the targets in the current experiment) is split between the two hemispheres such that stimuli to the left of fixation is initially projected to the right hemisphere, and stimuli to the right of fixation is projected to the left hemisphere [13,16]. One of the implications is that visual fields start immediately to the left and right of fixation [4].

the contributions of hemispheric asymmetry and perceptual learning on word length effects in the two cerebral hemispheres. In a lexical decision task, we briefly presented 3- and 6-letter Hebrew words. The words had either the same first two letters (as in *DO*G-*DO*UBLE in an English example) or the same end two letters (C*AT*-THRO*AT*). Fixation point for the same-first letters fell after the first two letters (DO*G, DO*UBLE), such that either one or four letters were initially projected to the right hemisphere via the LVF (see the upper panel of Fig. 1). If reaction times are slower for the longer words, this would show that hemispheric dominance does play a role in the length effect. For the same-end pairs, fixation point fell before the last two letters (C*AT, THRO*AT), such that either 1 or 4 letters were initially projected to the LH via the RVF (see the lower panel of Fig. 1). For these targets, we predicted that performance would differ as a function of word length due to the effects of perceptual learning.

2. Materials and methods

2.1. Participants

Twenty-three native Hebrew-speaking undergraduates and postgraduates at the Hebrew University of Jerusalem (10 male, 13 female) participated in the experiment. All of the participants had normal or corrected to normal vision and were between the ages 19–34 (mean age 24). All were rated as right handed by the Edinburgh Handedness Inventory [20] with mean score 92, range 70–100. Each participant received an honorarium for his/her participation.

2.2. Stimuli

Eighty Hebrew words and 80 non-words were used as stimuli. Words were taken, with permission, from the Hebrew Word Frequency DataBase (Alexandra McCauley, University of Edinburgh, www.cogsci.ed.ac.uk/~alexmcca/database.html). Forty words had 3 letters and 40 had 6 letters. The words were selected such that half of the 3-letter words had the same two initial letters as half of the 6-letter words (same first letters words), and the rest had the same two final letters (same final letters words). Thus we had 4 sets of words, each containing 20 words: 3-letter same-first words, 6-letter same-first, 3-letter same-last and 6-letter same-last. All four sets were matched for frequency (mean 4.4 per million words). The non-words were generated from another word pool by changing one letter, such that the non-words were legal and pronounceable. Non-words were also made of 3 and 6 letters with same-first or same-last letters in equal proportion.

The stimuli (words and non-words) were presented in Hebrew Fixed System lower case font, size 12 points. The width of the stimuli did not exceed 0.8° of the visual angle. The letters appeared black on a light grey background for comfortable reading. The stimuli were presented for 150 ms in the centre of the screen. The same-first targets were presented such that the first two letters (which were identical in the 3- and 6-letter words) were projected to the right of the fixation point (see Fig. 1), and the rest (1 or 4 letters) were presented to the left. The same-last targets were presented such that the final two letters were projected to the left of a fixation point, and the rest (1 or 4 letters) were presented to the right.

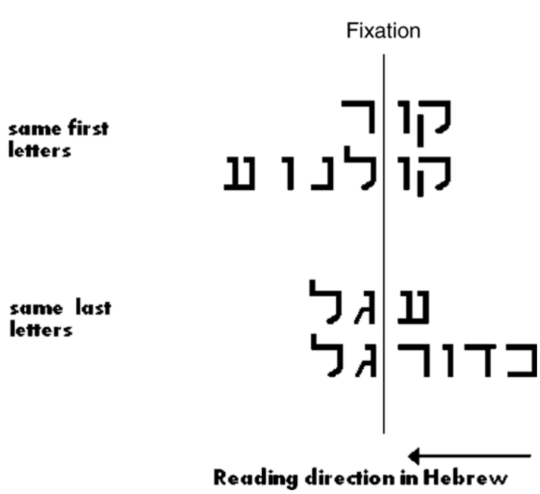

Fig. 1. An example of "same first" and "same last" stimuli used in the experiment for words of 3- and 6-letters long.

2.3. Apparatus and procedure

Each session began with 24 practice trials of centrally presented letter strings, where the task was to perform lexical decision. The practice trials presented 3- and 6-letter words and non-words in lower case letters. In the experimental trials, every target stimulus was presented once. Each of the 8 experimental groups (target wordness: word, non-word, target length: 3 and 6 letters, and position of shared letters: initial or final) repeated 20 times. There were therefore 160 experimental trials for each subject. The stimuli were presented in a random order.

Stimulus presentation was controlled by an IBM Pentium computer, 586 processor, on 17 in. SVGA display. The subjects sat at a viewing distance of 50 cm, with the head positioned on a chin rest. The experiment was designed using Super-Lab version 2.

Each trial began with a + appearing in the centre of the screen for 400 ms. For the first trial, the + remained for 2000 ms and disappeared when the target word was presented. The + would again reappear to allow projection of the next target word. Targets were briefly presented for 150 ms (either a word or a non-word) in screen centre, in the way described above. The subject's task was to decide, as quickly and as accurately as possible, whether the stimulus was a legal Hebrew word or a non-word. Subjects responded by pressing one of two available response keys with two fingers of the right hand, labelled 'word' and 'non-word' on a standard 'QWERTY' keyboard. For half of the subjects the response 'word' was made by pressing the 'N' key, and 'non-word' by pressing the 'V' key. For half of the subjects the response keys were reversed. The first 12 subjects were assigned to one of the two response options, and the remaining 11 to the other option.

The importance of fixating on the focus point during the task was emphasised.

3. Results

RTs of less than 200 ms and more than 1200 ms were discarded either as anticipatory or excessively lengthy (discarded trials occurred infrequently, less than 1.5% of the total responses). Mean reaction times and error rates are given in Table 1. Only correct responses were analyzed with regard to reaction times. The within-subjects factors were target lexicality, word length (3- or 6-letter strings) and position of shared letters (same initial letters or same final letters).

3.1. Reaction times to words

Word length significantly affected lexical decision latency
'$F(1,22) = 5.12$, $P < 0.05$). RTs for 6-letter words were significantly longer (mean = 486 ms) than those of 3-letter words (mean = 452 ms).

The interaction between word length and position of the shared letters was also significant ($F(1,22) = 4.13$, $P < 0.05$), as shown in Fig. 2. Bonferroni post hoc comparisons ($P < 0.05$) yielded that although there were significant length effects for both conditions of position of shared letter, it was greater for the same first position, where the variation in word length (1 letter for 3-letter words and 4 letter for 6-letter words) occurred in the LVF.

Table 1
Mean reaction times and % of errors as a function of target lexicality, position of shared letters and word length

	Position of shared letters		3-letters	6-letters
Words	Same first	Mean RT	453	498
		(SD)	(92)	(89)
		% errors	8	14
	Same last	Mean RT	452	474
		(SD)	(81)	(82)
		% errors	12	14
Non-words	Same first	Mean RT	519	565
		(SD)	(118)	(120)
		% correct	5	14
	Same last	Mean RT	522	570
		(SD)	(131)	(125)
		% correct	6	13

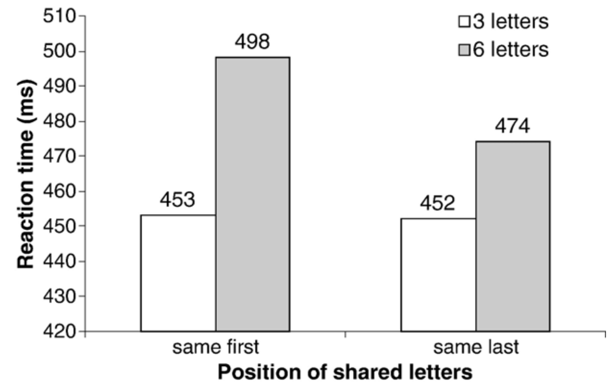

Fig. 2. Response times for words as a function of position of shared letters and word length.

3.2. Error scores for words

Word length significantly affected lexical decision accuracy ($F(1,22) = 5.2$, $P < 0.05$). Error scores for 6-letter words were significantly higher (mean = 14%) than those of 3-letter words (mean = 10%).

The interaction of the position of shared letters with length was also significant ($F(1,22) = 4.25$, $P < 0.05$). Length effect was found only for same-first letters pairs, where the length variation (1 letter for 3-letter words and 4 letters for 6 letter words) was in the LVF (based on Bonferroni post hoc comparisons).

3.3. Reaction times to non-words

There was a statistically significant main effect of non-word length ($F(1,22) = 6.29$, $P < 0.05$), with 3-letter non-words responses (mean = 520 ms) being faster than 6-letter non-word responses (mean = 567 ms). The interaction of non-word length and position of shared letters was not significant.

3.4. Error scores for non-words

Non-word length significantly affected lexical decision accuracy ($F(1,22) = 6.59$, $P < 0.05$). Performance for 3-letter non-words was significantly less erroneous (mean = 5% errors) compared to 6 letter non-words (mean = 14% errors).

4. Discussion

In a lexical decision task, we showed that for word stimuli, there was a significant interaction between word length and the position of the shared letters of the 3- and 6-letter Hebrew words that served as stimuli. When presenting the word such that the variation in length occurred to the left of the fixation point (1 letter for the 3-letter words and 4 letters for the 6-letters words; see Fig. 1), performance differed for the different-length words, and this length effect was bigger than the homologous length effect to the right of fixation, although this was significant as well. This interaction was found in both measures of performance, RT and accuracy. The existence of such interactions can only be explained if the representation of the fovea is initially split across the cerebral hemispheres. The lack of such interaction for non-words is in accordance with previous studies, which reported non-word length effects in both visual fields [9].

Because Hebrew is read from the right to left, different patterns of eye landings should have been developed for Hebrew readers (this argument was supported in [8]). However, if these different patterns were the only source of word length effect, as suggested by Nazir [17], Hebrew readers should have generated a length effect to the right, but not to the left of fixation. Our results clearly show that this is not the case: Hebrew readers, like English readers, showed a stronger length effect to the left of fixation, although there was as well a significant length effect to the right of fixation. That implies that both hemispheric dominance and scanning habits affect reading times in Hebrew.

The reported results are not in line with a previous study that manipulated letter case, word length and hemifields in Hebrew [15], where length effects were found only for the LVF. Perhaps the mixed-case presentation decreased the natural reading direction effects, or perhaps because shorter words were used (up to 5 letters), length effects did not emerge as opposed to the stronger manipulation (3- versus 6-letters) employed in the current research. Another difference is that in Lavidor et al.'s [15] study, presentations were fully lateralised, which might result in different length and hemifield interaction patterns.

The SERIOL model [21] allows an account of both the English and Hebrew patterns. In the model, an activation gradient at the feature level creates a serial firing at the letter level. This gradient is such that activation decreases from the first letter to the last letter. For example, for the stimulus CHART, the feature units representing C attain the highest activation, the features representing H have the next highest activation, and so on, with T's features having the lowest activation. These varying inputs to the letter level then cause staggered firing of letter units. That is, the unit representing C fires first, then H, then A, R, and T.

The formation of the activation gradient varies with hemisphere, due to the relationship with the acuity gradient. In the early cortical visual areas (called the edge level of the model), it is well known that the number of neurons in representing a fixed amount of space (acuity) decreases as eccentricity increases. Thus, taking activation level to be the total amount of neural activity representing a letter, a letter's activation at the edge level decreases as eccentricity increases. Note that for a left-to-right language, the acuity gradient matches the activation gradient in the RVF/LH (i.e., both are decreasing from left to right). Therefore, the acuity gradient can serve as the activation gradient in the RVF/LH. In contrast, there is a mismatch in the LVF/RH (where acuity increases from left to right). Therefore, special processing is required in the RH to invert the acuity gradient, as follows. Strong bottom-up excitation from the edge to the feature level raises the activation of all letters. Strong left-to-right lateral inhibition within the feature level inverts the acuity gradient. That is, the first letter inhibits the second letter, the first and second letters inhibit the third letter, etc. Thus the first letter attains a high activation level (due to strong excitation and no lateral inhibition), and activation decreases from left to right (due to the lateral inhibition).

For a long string in the LVF, this left-to-right inhibition may fail to produce a smoothly decreasing activation gradient. The activation of the second and third letters may be too low (due to strong inhibition from the first letter). The activation of letters near fixation may be too high, because inhibition may fail to counteract the increasing acuity. This non-optimal gradient would then result in a degraded encoding of letter order, causing increased settling time at the word level, thereby creating a length effect.

In a right-to-left language, the acuity gradient mismatches the activation gradient in the RVF/LH, not the LVF/RH. Thus, the SERIOL account predicts that there should be a RVF/LH length effect in Hebrew, as was indeed observed in the present experiment.

For LVF presentation in a right-to-left language, the acuity gradient can serve as the activation gradient, as for RVF presentation in a left-to-right language. However, in the right-to-left LVF case, orthographic information must be transferred to the LH, unlike the left-to-right RVF case. Under the assumption that such callosal transfer occurs at the feature level and preferentially degrades the representation of the least activated letters, feature-level final letters will have lower activations (than for left-to-right RVF presentation). The lower input levels to the letter units representing the final letters will then cause them to take longer to fire. Therefore, a length effect emerges for right-to-left LVF presentation.

This analysis is summarized in Table 2. Thus we propose that acuity-gradient inversion creates a length effect due to non-optimal activation pattern across the letter features. Callosal transfer creates a length effect via reduced input levels to letter units. When neither factor is present (i.e.,

Table 2
Processing required by reading direction and visual field under the SERIOL model

	LVF	RVF
Left-to-right	Inversion/transfer	Neither
Right-to-left	Transfer	Inversion

Inversion refers to formation of the activation gradient from a mismatching acuity gradient, giving an increasingly non-optimal activation gradient as string length increases. Transfer refers to callosal transfer from the RH to the LH, resulting in reduced activation levels and delayed firing of letter units.

RVF presentation in a left-to-right language), no length effect emerges. When both factors a present (i.e., LVF presentation in a left-to-right language), we suggest that callosal transfer further degrades the non-optimal activation pattern, creating a strong length effect.

This analysis suggests that a different manipulation is required to remove LVF length effect in a left-to-right language than in a right-to-left language. In future work, we will test these predictions by applying both manipulation patterns in both visual fields in Hebrew. What we have clearly shown in the current study is that Hebrew readers, like English readers, showed a stronger length effect to the left of fixation, although there was as well a significant length effect to the right of fixation. That implies that both hemispheric dominance and scanning habits affect reading times in Hebrew.

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