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The flexibility of letter-position flexibility: evidence from eye-movements in reading Hebrew

Hadas Velan^{1,3}, Avital Deutsch², and Ram Frost^{1,4}

¹Department of Psychology, The Hebrew University

²The School of Education, The Hebrew University

³Department of Psychology, The University of Arizona

⁴Haskins Laboratories, New Haven, CT

Abstract

Hebrew provides an intriguing contrast to European languages. On the one hand, like any European language, it has an alphabetic script. On the other hand, being a Semitic language, it differs in the structure of base words. By monitoring eye movements, we examined the time-course of processing letter transpositions in Hebrew, and assessed their impact on reading different types of Hebrew words that differ in their internal structure. We found that letter transposition resulted in dramatic reading costs for words with Semitic word structure, and much smaller costs for non-Semitic words. Moreover, the strongest impact of transposition occurred where root-letter transposition resulted in a pseudo-root, where significant interference emerged already in first fixation duration. Our findings thus suggest that Hebrew readers differentiate between Semitic and non-Semitic forms already at first fixation, at the early phase of word recognition. Moreover, letters are differentially processed across the visual array, given their morphological structure and their contribution to recovering semantic meaning. We conclude that flexibility or rigidity in encoding letter position is determined by cues regarding the internal structure of printed words.

Keywords

TL; letter position coding; word-recognition; Hebrew; Morphology

In recent years, a large number of studies have consistently reported a relatively small cost of letter-transpositions (e.g., *jugde* - *JUDGE*) in terms of reading speed and accuracy, along with robust priming effects when primes and targets share all of their letters but two of them are transposed (e.g., Duñabeitia, Perea & Carreiras, 2007; Guerrero & Forster, 2008; Lupker, Perea & Davis, 2008; Perea & Carreiras, 2006; Perea & Lupker, 2003a, 2003b, 2004; Perea & Pérez, 2009; Rayner, White, Johnson & Liversedge, 2006; Schoonbaert & Grainger, 2004; and see Grainger, 2008, for a review). The transposed-letter (TL) effect reported in many languages was taken to suggest that the tolerance to changes in letter position (at least for internal letters) reflects *basic and primary* cognitive operations involved in visual word recognition. This view, however, was recently challenged by consistent findings from Hebrew and Arabic, demonstrating that reading in Semitic languages is severely hindered by letter transposition (Velan & Frost, 2007, 2009, 2011; Perea, Abu Mallouh, & Carreiras, 2010). In a series of experiments, Velan and Frost (2011) have further shown that TL effects

in visual word recognition are not only language-dependent but also stimuli dependent, so that even within one language -- Hebrew -- different letter-coding schemes are revealed depending on the internal structure of the base formsⁱ. The contrasting results from Semitic languages regarding enhanced sensitivity to letter-order have been attributed to the characteristics of Semitic morphological structure and the way it determines orthographic structure (see Frost, 2012, for a comprehensive theoretical discussion). This has substantial implications to modelling visual word recognition and the understanding of reading processes.

Note that there is some evidence that the TL effect in European languages might also be modulated by morphological structure, as transposition across morphological boundaries for both prefixes and suffixes were reported to reduce or even annul TL effects (e.g., Christianson, Johnson & Rayner, 2005; Duñabeitia et al., 2007). Nonetheless, there is also contrasting evidence that shows no differences in TL effects within and across morphological boundaries in English in both masked priming and eye-movement (Rueckl & Rimzhim, 2011; Masserang, 2010). More importantly, as a general argument, the cost of letter-transposition in Semitic languages (or rather the lack of them) cannot be attributed to the crossing of morphemic boundaries, since typically the changes in letter-order in the Hebrew or Arabic studies has involved an orthographically single bound morpheme -- the root -- which serves as one of the constituents of the base-form. Similarly, the differential sensitivity to letter-transposition in Semitic and non-Semitic languages cannot be attributed to the differences between transpositions of consonants and vowels, or to syllabic boundaries (Perea & Carreiras, 2006; Perea & Lupker, 2004; Lupker et al., 2008), since only orthographic adjacent consonants were transposed in studies that directly compared TL-effects in Hebrew vs. English (e.g., Velan & Frost, 2007, 2011).

One major controversy regarding the variant flexibility of letter position coding concerns *the time course* of linguistic modulation of orthographic processing. For example, it has been argued that the *primary* perceptual processes involved in visual word recognition universally result in ambiguous letter-position coding. The product of this noisy initial processing phase is then subsequently shaped by the properties of the language, and eventually produces cross-linguistic differences in TL priming effects (e.g., Norris & Kinoshita, 2012; Gomez & Silins, 2012). This view considers then the influence of linguistic factors related to language or stimuli to be relatively late, operating on a primary perceptual output that involves considerable uncertainty regarding letter-position. In contrast, several studies have shown that the distributional properties of letter combinations, which do differ across languages, modulate responses already at the very early phases of processing (e.g., Simos, Breier, Fletcher, Foorman, Castillo, & Papanicolaou, 2002; Solomyak & Marantz, 2010; Szwed, Vinckier, Cohen, & Dehaene, 2012). This view is compatible with findings showing that reading habits that are related to writing systems result in some form of perceptual learning, and can be traced to the early stages in the visual pathway (e.g., Nazir, ben-Boutayab, Decoppet, Deutsch & Frost, 2004). Thus, evidence concerning the *temporal* aspects of letter-position sensitivity has critical implications for understanding and modelling orthographic processing. The present paper addresses this question by monitoring how different stimuli modulate the cost of letter transposition in the different online measures of eye-movement in Hebrew.

Hebrew provides an intriguing contrast to European languages. On the one hand, its script is alphabetic like any European language. However, on the other hand, Hebrew words have two possible basic structures, “European-like”, and Semitic. Whereas some base-forms are

ⁱBy the term base -form we refer to the most basic morpheme, usually an independent word, which constitutes the form to which derivational and inflectional morphemes are added. For example the word read is the base form of readable, unreadable, rereading, etc.

morphologically simple as is the common case in European languages, most Hebrew base-forms are morphologically complex and have a characteristic internal structure. These words comprise two derivational morphemes: a root and a word-pattern. The root usually consists of three consonants. It represents the core meaning of the word, and is embedded in a phonological word-pattern which carries morpho-syntactic information and determines the word's prosodic and vocalic structure. These two morphemes (and therefore, their corresponding letters) are interwoven in a non-concatenated manner to produce most nominal and all verbal forms (see Shimron, 2006, for a detailed description). For example, the Hebrew word /maxsom/ (a "barrier") is derived from the root x.s.m (conveying the meaning of "blocking") and the word pattern /maC₁C₂oC₃/ (denoting masculine nouns, where each C indicates the position of a root consonant). In contrast, the Hebrew word /ʔagartal/, (a vase) is Persian by origin, is not root-derived, and thus does not have a Semitic word structure.

In a series of studies, Velan & Frost (2007, 2009, 2011) demonstrated that TL priming cannot be obtained for Hebrew base-forms with a Semitic structure; that is, with words that are derived from a root within a word-pattern. The intolerance of Hebrew to letter transposition was observed using the masked priming paradigm for single word recognition in which the effect of transposed primes was compared to those of orthographic control primes (Velan & Frost 2009, 2001). It was also observed in Rapid Serial Visual Presentation (RSVP) of sentence reading in which reading accuracy of sentences that included transposed nonwords was compared to the reading accuracy of intact sentences (Velan & Frost, 2007; 2011). Velan and Frost have argued that since in Hebrew several roots often share the same set of three consonants (or letters) but in a different order (e.g., l.x.ʃ (to whisper), x.l.ʃ (to dominate), ʃ.l.x (to send), x.ʃ.l (to forge) etc.), rigid coding of letter position is necessary for correct root identification. Velan & Frost (2011) have further shown that Hebrew base-forms that are morphologically simple, and do not contain a root morpheme (Hebrew words from non-Semitic origin such as /ʔagartal/), are processed similarly to base forms in European languages. For these words, robust and significant TL priming effects are obtained, as they are obtained in English, French, Spanish, or Basque. The contrasting TL effects for Semitic and non-Semitic Hebrew words seem to be related to the primary role of root letters in visual word recognition (see Frost, Kugler, Deutsch & Forster, 2005, for a detailed discussion). More important, these findings seem to suggest a genuine flexibility of the cognitive system in terms of whether letter-position coding is rigid or not, depending on the internal structure of the printed word.

This approach, however, stands in sharp contrast to most recent models of visual word recognition, which consider the profound tolerance of readers to changes of letter order within a word to be *primary* and universal, supposedly reflecting the special way in which the human brain encodes the position of letters in printed words at the early phase of orthographic processing (see Grainger, 2008, for a review, and Frost, 2012, for a discussion). The present paper addresses this controversy by tracking the *early* processing of printed letter strings by applying an online measure of tracking readers' eye-movements. As detailed above, previous experiments examining the TL effect in Hebrew used masked-priming for single words identification (Velan & Frost 2009; 2011) or Rapid Serial Visual Presentation for sentence reading (Velan & Frost, 2007, 2011). In the present study, we examined whether letter transposition in words with Semitic or non-Semitic structure incurs similar or differential costs in terms of the different eye-movement measures; those reflecting early versus more advanced processing.

The advantage of tracking eye-movement is anchored in its ecological validity as it enables to explore reading under relatively natural conditions. Moreover, it provides online measures that allow monitoring *the time course* of the different processes involved in word

recognition during reading (for a review see Rayner, 2009). Studies in English that investigated eye-movements in text involving transpositions revealed a relatively small cost of transposition of *internal* letters. For example, Rayner et al. (2006) have shown that reading speed decreases by 11% in comparison with a normally presented text when middle letters are transposed (See also White, Johnson, Liversedge & Rayner, 2008, for an effect of 5% in first fixation, and 18% for gaze duration.)ⁱⁱ. Johnson, Perea, & Rayner (2007) compared the effect of presenting transposed and substituted versions of target words in the parafovea, before the eyes actually land on the target words in the course of reading. Parafoveal information is known to affect foveal fixation duration, i.e. the amount of time a reader spends on a given word before leaving it for the first time in the natural course of reading (Rayner, 1998). Facilitation of fixation duration by parafoveal information is usually termed as ‘parafoveal preview benefit effect’. Johnson et al. (2007) showed that transposed letters lead to shorter fixations on target words relatively to substituted letters when compared to an identity baseline. The maximum cost observed for transposition was of 7% in gaze duration vs. a cost of about 11% for letter substitutions (see also Johnson & Dunne, 2012, for even smaller effects when transposed letters resulted in a real words and Johnson, 2009 who demonstrated interference only in eye-movement late measures). Recently, Johnson (2007) compared parafoveal preview benefit for transposition and substitution of letters, showing that transposed consonant letters lead to shorter fixations on target words in first fixation duration relative to substituted letters, with no difference between identical and TL previews (interference of 4% in the transposed preview). However, in gaze duration, the identity preview yielded significantly shorter viewing durations in comparison to both transposed and substituted letters (8.5% and 11%, respectively). Note that this relatively low cost was obtained even though the letters transposed were not adjacent (see also Liversedge & Blyth, 2007, for a review). Given these findings, investigating the costs of letter transposition of Semitic vs. non-Semitic words using on line measures of eye-movements in Hebrew is especially intriguing, since it provides a direct comparison of the on-line cost of letter transposition for words with a complex stem (the typical Semitic structure) vs. morphologically simple stems (the “English-like” structure).

Our study was designed, therefore, to examine how reading measures of TL words are affected by the words’ internal structure, particularly the ability to extract a root morpheme. We thus compared the online reading of sentences containing TL Hebrew words of three types: 1) root-derived words where root-letter transposition resulted in a non-existing root (TL pseudo-root condition); 2) root-derived words where root-letter transposition resulted in another existing root (TL existing-root condition), and 3) similar to Velan & Frost (2011), morphologically simple Hebrew words which do not have the Semitic root and word-pattern structure, and thus resemble the simple stem structure that characterizes European words (simple-word condition). Although all these types of words were previously examined across the various studies conducted in Hebrew (Velan & Frost, 2007; 2009; 2011), the current study allows direct comparisons of the effect of letter transpositions on each of the various types of words, in a within-subject within-language design, and most importantly within a single experimental procedure – one that was not previously applied in Hebrew and has the advantage of reflecting on-line processes of root extraction and lexical access. By contrasting the condition where the root letter transposition resulted in an existing (albeit incorrect) root, to a condition where the transposition resulted in a pseudo, non-existing root, we examined how root lexicality modulates on-line processing as revealed by patterns of eye-movements. Note that in both cases, the transposition of letters created an orthographic

ⁱⁱThese values refer to transposition of internal letters, as was the case in all previous studies in Hebrew, as well as in the current study. Transpositions involving ending and particularly beginning letters are much more costly (Rayner et al., 2006), as these letters define the words’ boundaries. Furthermore, in these studies transposition of letters took place across the entire sentence, and did not involve a single target word as was the case in the current study.

letter sequence that was a nonword. However, whereas in the former condition, a legal root-morpheme could be extracted allowing access to a legal lexical root unit, in the latter it could not.

When monitoring eye-movements, few common online measures are typically used to follow the time course of processing printed information: (1) first fixation duration, i.e., the duration of the first fixation on a given target word, (2) gaze duration, i.e., the sum of the durations of all fixations made on a target word from the first time the reader's eyes land on the word until the eyes move to a preceding or following part of the sentence, and (3) total time, i.e., the sum of all fixations on the target word, including regressions and re-reading the sentence. While first fixation duration and gaze duration reflect *early processes* of initial letter coding and competition between lexical candidates, total time is considered to reflect *late processes* attributed to a verification stage, where words are fully identified and integrated into the sentence context. The comparisons between these measures enabled us to explore the time course of TL interference for the different types of Hebrew words.

In order to achieve a more comprehensive description of eye movement behaviour we also report (1) the percentage of regressions that have been made out of the target word into preceding words, initiating re-reading of the sentence (or parts of it) and (2) the percentage of regressions made into the target word from following words, directly affecting the measure of total time. Furthermore, spillover effect, i.e., the duration of the first fixation made on the following word (target + 1) immediately after the reader left the target word, was examined to see whether difficulties in processing the target were carried to the next word as a function of the different types of words.

Our predictions were straightforward: if the internal structure of words indeed modulates the flexibility or rigidity of the letter-position coding scheme *online*, so that rigid letter-coding is adopted for root-derived base forms, and flexible letter-position coding is adopted for simple base-forms, then *significant and large interference of letter-transposition will be observed for root-derived base-words, while small effects, if any, will be revealed for morphologically simple words*. More important, the differential interference for words with and without internal structure will be revealed already in the early measures of reading -- first fixation. In addition, we hypothesized that if the successful location of a known root morpheme is the primary target of word processing, then the strongest impact of transposition will occur in the TL pseudo-root condition. This is because the initial process of root extraction will result in a dead-end -- a nonexistent root -- thereby preventing lexical access.

Method

Participants

thirty-two students from the Hebrew University participated in the experiment for course credit or for payment. The participants had either normal or corrected to normal vision and were native speakers of Hebrew.

Apparatus

eye movements were recorded via the SR Research Ltd. (Canada) EYELINK II eye-tracker, a video based tracking system that samples pupil location at the rate of 500 Hz. The sentences were presented on a CRT computer monitor (View Sonic P225F, 22") and controlled by an Intel Pentium HD-3000 computer. Eye-movement data was collected by a second Intel Pentium 4D-3000 computer interfaced to the eye-tracker and synchronised with the stimulus-control computer. Although viewing was binocular, only data from the right eye were recorded. The spatial resolution of the eye-tracking system is less than half a

degree. Participants were seated 60 cm from the video monitor, with 1.8 characters subtending 1° of the visual angle (Arial font size 16).

Stimuli and Design

thirty-six target words were used in the experiments, and these consisted of three types of Hebrew words: 1) twelve root-derived words where the TL root created a non-existing root (TL pseudo-root condition); 2) twelve root-derived words where the TL root created a different, irrelevant, existing-root (TL existing-root condition); and 3) twelve morphologically simple words that did not contain a root and a Semitic word-pattern (Simple word condition). When selecting the stimuli, we had significant constraints: The first and last letters of all targets words were not transposed. Target words were of 4 to 6 letters long. In addition, given that TL effects might be significantly reduced if morphemic boundaries are crossed (Christianson, et al., 2005; Duñabeitia et al., 2007), we ensured that only two adjacent root-letters were transposed, so that the continuity of the letters of the root was not orthographically compromised by letters belonging to the word-pattern. Adjacent interior letters were also transposed in the morphologically simple words. In half of the targets transposition involved the second and third letter, and in half the third and fourth letter. As noted earlier, all transpositions resulted in *nonwords*. Target words of the three types were matched in length, frequency and neighbourhood density (see Table 1).

The 36 target words were embedded into 36 single-line sentences of 7–9 words each with an average of 7.9 words ($SD = .77$). Target words never appeared at the beginning or at the end of the sentence nor did they appear with any clitics. Target words in each sentence were either presented intact or had letter transpositions, so that each participant saw 18 intact sentences and 18 sentences with transposed target words. To reduce effects of expectation, the sentences were constructed so that the target words could well be integrated in the sentential context, but were not highly predictable by its prior context.

In order to ensure that the critical words were plausible within the sentential context but not highly predictable, we conducted two norming procedures:

1. Rating of plausibility: Fourteen subjects read the sentences and had to rate their plausibility on a 1–7 scale (1=not plausible; 7= very plausible). In addition to the experimental sentences, subject also rated 8 filler sentences, half of which were highly plausible and the rest highly implausible. The overall mean plausibility rating was 6.03. None of the sentences received a mean of less than 3. The difference between the three types of sentences was not significant ($F_{(2,26)}=1.133$ $p<0.29$).
2. Predictability test: Twelve subjects were given the test sentences in which a blank space replaced the target words and were asked to provide a single word that completes the sentences, so that the sentence created would be logical and plausible. Of all of the completions, only 9% included the actual target word, with no statistical difference between word type ($\chi^2=3.29$, $p<0.2$).

Subjects who participated in the predictability or the acceptability tests did not participate in the experiment. An example of the sentences used in the experiment is presented in Table 2 (the sentences employed in the experiment are available at <https://sites.google.com/site/hadasvelan/Stimuli.TL.EyeMov.pdf>).

The sentences were divided into two lists, and sixteen different participants were tested in each list. This procedure allows each participant to provide data points in each experimental condition while avoiding stimuli repetition effects.

Procedure

At the beginning of the experiment, the eye-tracking system was calibrated for each participant using 9 locations points (distributed across the centre, the four edges, and at the centre of each of the horizontal and vertical borders of the screen). After calibration, the participants read 6 practice sentences to become familiarised with the procedure. Subjects were told that some of the words contain jumbled letters and that they would probably be able to identify them. They were instructed to focus on understanding the meaning of the sentences (see also White et al., 2008). Each trial started with a fixation point in the middle of the right-hand side of the monitor (Hebrew is read from right-to left), the location of which coincided with the location of the first letter of the sentence. Once the participant focused on the fixation point, the calibration was verified and the target sentence was presented. The target sentence was displayed until participants finished reading the sentence and moved their eyes towards a green square at the bottom left hand corner of the screen. Seeing the participant's eyes fixed on the green square signalled to the experimenter to start the next trial. Participants were instructed to read the sentences for comprehension. Seventeen percent of the sentences were followed by a yes/no comprehension question to ensure that the sentences were being read for meaning. Experimental sentences were presented in random order.

Results

All trials in which the target word was skipped were eliminated from the analysis (2% of the data). Fixations under 140 ms and over 800 ms were discarded (only 1 trial was excluded). In addition, 1% of the trials were excluded due to tracker loss or blinks on first-pass reading of the target word. Trials in which the yes/no comprehension question scored an error response were eliminated from the analyses. The maximal error rate subjects had was 1 error out of 6 questions (17%), and the mean error rate was slightly less (15%). Separate means were analysed for each participant and each item for each of the measures: first fixation, gaze duration, total time and spillover. For each of these measures, outliers of 2.5 SD above or below the mean (for each participant in each word type and TL condition) were replaced by the cut-off value and the mean was recalculated. There was a total of 6.5% of outliers across all measures. No significant differences in the distribution of outliers between the various conditions in each of the eye-movements' measures were found. The means fixation durations of the various measures are presented in Table 3.

The effect of letter transposition was measured in comparison with the intact, baseline condition. Since the baseline was different for the three conditions (due to different target words) the TL effects were calculated as a proportion:

$$\frac{\text{transposed condition} - \text{intact baseline condition}}{\text{intact baseline condition}}$$
. Note that positive values indicate inhibitory effects. The TL effects in proportions are presented in Figure 1.

As can be seen in Figure 1, and in line with our prediction, the interference caused by letter transposition was substantially modulated by the internal structure of the printed words, already at the earliest measures of processing, and increased as reading time progressed. Interference in the TL pseudo-root word condition was robust and apparent already at first fixation (14%). It increased during first pass to a very large 41% for gaze duration, and progressed to a staggering 70% in the late measure of total time. In contrast, when transposition created an existing root (the TL existing-root condition), so that a known root could be extracted from print, no interference was found for first fixation. For gaze duration, interference reached 23%, levelling up to the interference rate of the TL pseudo-root during the late measure (71%). For non-Semitic simple words without internal structure, interference was significantly smaller. It was virtually nonexistent at first fixation. It reached

a level of 13% for gaze duration, with a maximal level of 33% for the late measure, less than half of that found for Semitic words.

Fixation durations in each of the three measures were subjected to a two way ANOVA in which the transposition manipulation (intact, TL) was one factor, and word type (simple, TL pseudo-root, TL existing-root) was another. Error variance was calculated over participants (F_1) and items (F_2). Analyses are reported in Table 4. A series of planned comparisons examining the TL effect in each word type is presented in Table 5. All statistical analyses were performed on the raw values of RT (not on the proportions) data.

Across the two early measures (first fixation duration and gaze duration), letter-transposition led to an increase in viewing duration. In the first fixation duration measure, planned comparisons revealed that the inhibitory effect of 32 msec for TL pseudo-root word type was significant for participants as well as for items ($p < 0.003$, for both analyses). In the gaze duration and total time measures, planned comparisons revealed a significant inhibitory effect for each of the word types, for both subject and item analyses (with one exception of gaze duration item analysis of simple word type, in which $p < 0.077$). See Table 5.

We assessed the differences in the amount of interference effect between the various word types in the various measures: for first fixation duration, the 13% difference between the TL pseudo-root condition and the simple word condition was significant ($p < 0.04$, $p < 0.01$, for F_1 and F_2 , respectively). The difference between this condition and the TL existing-root condition was significant for F_2 ($p < 0.01$), but only marginally significant for F_1 ($p < 0.067$). In the gaze duration measure, only the difference of 28% between the simple word type and the TL pseudo-root word type reached significance ($p < 0.01$, for F_1 and F_2). In the total time measure, the differences in TL effect between the simple and each of the root type derived words were significant (see full statistical data in Table 6). Apparently, the increase in total time was in accord with an increase in the percentages of ‘regressions in’ and ‘regressions out’ of the target word in each of the TL conditions (Regressions in: $p < 0.05$ for F_1 and F_2 for all word type in each of the TL conditions; Regressions out were less consistent, see Table 6). In general the *raw number* of ‘regressions in’ was about three times higher than that of ‘regressions out’.

A spillover effect appeared for TL existing-root and simple word conditions. This effect reached statistical significance for subjects and items in the simple word condition ($p < 0.05$ for F_1 and F_2), but only across subjects in the TL existing root condition ($p < 0.05$, $p < 0.13$ for F_1 and F_2 respectively).

Discussion

The present study examined the impact of letter transposition on reading sentences in Hebrew while monitoring readers’ eye movements. The results converge with our previous masked-priming and RSVP findings, indicating that transposition *within* the morphological unit of the consonantal root hinders word recognition. This interference thus cannot be attributed to morpho-orthographic effects caused by crossing morphological boundaries, since transposition took place always between adjacent root letters. Furthermore, it cannot be attributed to morpho-phonological factors as transposition took place only between consonantal units. The observed interference thus reflects the deleterious influence of destroying the *sequence* of the root letters that point to a lexical root unit. Note that the position of actual slots of root letters within a word remained unchanged. Thus, transpositions changed the *identity* of specific letters assigned to each slot. The present results provide then additional support to our claim that the internal structure of words modulates sensitivity to letter position in Hebrew (Velan & Frost, 2011). They provide,

however, important additional insights regarding the time course of morphological processing during reading.

The most striking finding of our study is the modulation of transposition interference by the different types of Hebrew words, as processing time progresses. Considering the very early measure of first fixation, significant interference was found only when the printed stimuli had a Semitic structure, and transpositions resulted in pseudo-roots. This finding suggests that the processing system of Hebrew readers differentiates between Semitic (root-derived) and non-Semitic (simple) forms already at first fixation, namely, at an early phase of word recognition.ⁱⁱⁱ Once a Semitic word structure has been detected, the primary goal of processing is the extraction of an existing root *regardless* of the lexicality of the *full letter sequence*. This early phase of processing the letter string is, therefore, blind to full orthographic lexicality (i.e. whether a given root can be legally combined with the given word-pattern to create an existing, meaningful word). It searches only for three letters that fit a known root, even if the full letter sequence is a nonword. Consequently, if the transposition of letters results in a non-existing, pseudo-root, further processing is hindered, as reflected by the significant cost in the pseudo-root condition relative to the intact condition, already in the first fixation duration. Note that the location of root letters is cued by the well-learned skewed distribution of the word-pattern letters. Word-patterns in Hebrew can begin and end with a very restricted number of consonants (mainly /h/, /m/, /t/, /n/, /l/ for initial letters and /h/, /n/, /t/ for a final letter), and these determine a set of conditional probabilities regarding the order and identity of subsequent consonants and vowels. The word-pattern letters “point,” therefore, with reasonable accuracy, to the letter-slots belonging to the root. Since non-Semitic (simple) words do not have a well-defined internal structure, as they are not derived from a root and a word-pattern, readers have sufficient orthographic cues leading them to process the entire string of letters as a single unit rather than applying the typical morphological decomposition process. Consequently, these words are unaffected by letter transposition during the initial stage of processing.

As processing advances, and possible additional fixations on words occur (as reflected by gaze duration), the differential impact of words’ internal structure on TL interference becomes even more conspicuous. Some interference (13%) is revealed now for simple words, and these values are similar to the costs reported for TL words in English (e.g., White et al., 2008, when both high- and low-frequencies are taken together). This cost is usually ascribed to processes of verification and integration when the system recognises the difference between the real word and the transposed one. The costs incurred for Semitic words, however, were significantly larger: 23% for root-based words where transposition resulted in an existing root, and 41% for root-derived words where transposition resulted in a pseudo-root. These findings demonstrate again that the location of a legal root morpheme is the main aim of processing the letter string, once it is recognised as having the typical Semitic structure.

The late measure of total time reveals a dramatic difference in letter-transposition interference for Semitic and non-Semitic words. In general, the increase in total time was in accordance with increased number of regressions into and out of the target word. However, the total number of ‘regressions in’ was higher than the number of ‘regression out’, indicating that letter-transpositions indeed initiated re-reading of the sentence (or parts of it), but more often they incurred longer second reading latencies of the target area itself. The cost obtained for simple words was 33%, somewhat larger than the 27% cost for total time

ⁱⁱⁱNote that White et al. (2008) report a significant TL effect for First Fixation duration in English, i.e., non-Semitic language. However this analysis combines both internal and external letter transpositions. Inspection of the raw fixation durations for the various locations suggests that the significant effect first fixation stems from transpositions in beginning and ending external letters.

obtained by White et al. (2008) for English, but less than half the cost incurred for Semitic root-derived words, where interference reached the staggering value of 70%. Interestingly, for the late measure of total time, the pseudo-root and the existing root conditions did not differ, showing identical cost of letter transposition. This result provides important insight regarding the online processing of root letters in reading. The overall pattern of interference revealed in our study suggests that whereas the initial fixations at first pass are aimed simply at locating a known tri-literal root unit *regardless of orthographic lexicality*, as processing progresses, orthographic lexicality imposes its constraints on the root identity. These constraints require that the specific tri-literal sequence of a given root be registered, and furthermore, that this specific root can indeed be embedded in the given word pattern creating the specific printed stimulus. This constraint is reflected by the appearance of interference for the existing-root condition in the first-pass measure of gaze duration, as the existing, irrelevant TL root, did not fit the transposed stimulus from which it was extracted. Thus, at later phases, reflected in total time, a “wrong” root is just as bad as a pseudo-root, and the cost of transposition in these two types of nonwords is, therefore, identical.

Interestingly, a spillover effect of TL was not apparent for the TL pseudo-root condition but only for the TL existing root, and most strongly for the TL simple word conditions. The absence of spillover effect for the pseudo-root condition further demonstrates that the failure to extract a real root immediately inhibits the on-line process of word recognition, and thus has its main effect on first pass reading. The size of the spillover effect increases in cases where TL has a relatively weaker effect on first-pass reading, and reading continues even though a transposed-letter word was encountered.

Our present study thus provides important insights regarding the processing of letter sequences and the flexibility of the cognitive system in being either rigid or flexible about letter-position encoding, depending on the context. Mostly, the results provide critical information regarding *the time course* of letter-position sensitivity. The present evidence from eye-movements in Hebrew is especially compelling, since it reflects the initial phases of orthographic processing that are presumably not governed by a conscious strategy or revealed by off-line measures. The findings obtained for the different types of Hebrew words clearly demonstrate that letters are *differentially* processed across the visual array given their morphological status and their relative contribution to semantic meaning at the earliest phase of processing. Thus, the distributional characteristics of individual Hebrew letters control the planning of saccades, fixations, and regressions, and these seem to be entirely determined by the different statistical properties of words with or without Semitic structure. These findings are in line with claims that the idiosyncratic distributional properties of letters in a language result in perceptual learning -- a means to facilitating fast and efficient recognition of visual configurations that are frequently encountered by the organism (e.g., Sigman & Gilbert, 2000; Gilbert, Sigman, & Crist, 2001). These findings also converge with previous data reported by Deutsch and Rayner (1999) demonstrating that landing positions on printed Hebrew words are modulated by the location of the first root letter within the word, and with findings showing that root information presented to the parafovea (see Rayner, 1998, for a review of parafoveal presentation and the boundary technique) results in robust parafoveal preview benefit effects (Deutsch, Frost, Pollatsek, & Rayner, 2000; Deutsch, Frost, Pelleg, Pollatsek, & Rayner, 2003). Whether cross-linguistic differences in letter coding can be demonstrated also parafoveally, requires, however, further investigation.

To conclude, we suggest that the processing of letters and the flexibility or rigidity in encoding their position is determined by cues regarding the internal structure of printed words. These cues concern the distributional properties of specific letter or letter sequences, and their relative contribution in conveying morphological information and semantic

meaning. This suggestion accords with the view that the TL effect reflects a specific phenomenon that characterizes visual word recognition, rather than a general perceptual principle (Duñabeitia, Dimitropoulou, Grainger, Hernández, & Carreiras, 2012). As such it may be modulated by language specific characteristics. This approach contrasts with claims of temporal modularity (see Andrews, 2006) in modelling visual word recognition, by which morphological and semantic considerations come into play *subsequent* to the stage of orthographic processing, in which letter-position is universally flexible (e.g., Davis, 2010; 2012; Norris & Kinoshita, 2012). Our approach also contrasts with recent suggestions that, similar to primates, orthographic processing in humans is akin to visual object processing, so that the linguistic properties of letters do not play a role in the early phase of orthographic coding (Grainger, Dufau, Montant, Ziegler, & Fagot, 2012). Our findings thus demonstrate that the nature of orthographic processing *from the onset* is determined by how the language morphology determines the statistical characteristics of orthographic structure.

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Figure 1.
Proportion of the Interference effects induced by letter transposition

Table 1

Means of lexical characteristics for the Items used in the experiment

	TL pseudo-root	TL existing-root	Simple	F	P
Length (no. of letters)	4.75	4.83	4.42	2.2	.129
Frequency ^{iv}	6.5	7.25	5.88	< 1	
Orth. Neighbours (no.)	2.42	3.83	2.33	2.4	.106

Note: The reported word frequency are the frequencies per million

^{iv}Taken from Frost & Plaut (2005).

Table 2

Examples of the stimuli used in the experiment (words in parenthesis are the words presented in the transposed letter condition)

<i>Target Type</i>	
TL pseudo-root	<p>עומר הציב מחסום (מסחום) זמני ליד משאבה מקולקלת של דלק.</p> <p>Target: mxswm (/maxsom/, a barrier)</p> <p>Root: x.s.m TL root: *s.x.m</p> <p>Omer placed a temporary barrier next to the broken petrol pump.</p>
TL existing-root	<p>השר החליט על הפחתה (הפתחה) בייבוא מוצרי הלבשה מצרפת.</p> <p>Target: hpxth (/hafxata/, a reduction)</p> <p>Root: p.x.t TL root: p.t.x</p> <p>The minister decided on the reduction of clothing import from France.</p>
Simple	<p>הילד הקטן שבר אגרטל (ארגטל) גדול עם ברזל ארוך.</p> <p>Target: ?grəl (/?gartal/ “a vase”)</p> <p>The little boy broke a big vase with a long pole.</p>

Table 3

Means of fixation durations for the target word (and SD) and effect size in ms in the various eye-movement measures in each condition as well as number of regressions (and percentages out of total number of regression across all conditions) made into and out of the target words

	TL pseudo-root		TL existing-root		Simple	
	Intact	TL	Intact	TL	Intact	TL
first fixation duration	228 (35)	260 (59)	231 (44)	234 (36)	238 (46)	240 (56)
<i>TL effect</i>	-32		-3		-2	
gaze duration	271 (52)	383 (134)	303 (68)	372 (121)	292 (64)	329 (78)
<i>TL effect</i>	-112		-69		-38	
total time	330 (99)	561 (187)	393 (126)	671 (329)	335 (93)	446 (160)
<i>TL effect</i>	-231		-277		-111	
Spillover	245 (42)	251 (56)	230 (47)	249 (53)	228 (35)	251 (48)
<i>TL effect</i>	-5		-18		-22.51	
regressions in	23 (7%)	73 (23%)	38 (12%)	94 (30%)	23 (7%)	62 (20%)
<i>TL effect</i>	-50		-56		-39	
regressions out	14 (11%)	28 (22%)	21 (16%)	31 (24%)	14 (11%)	21 (16%)
<i>TL effect</i>	-14		-10		-7	

Table 4

Overall ANOVA for each measure

	Transposition			Word Type			Transposition × Word type			
	F	MSe	p	F	MSe	p	F	MSe	p	
Early Measures										
first fixation duration	F_1	9.82	762	.004*	1.44	1444	.24	3.11	1462	.052
	F_2	6.61	443	.015*	1.49	573	.24	4.2	443	.024*
gaze duration	F_1	36.79	6924	.0001*	3.17	3835	.0491*	4.26	5194	.019*
	F_2	38.68	2607	.001*	1.38	3092	.26	3.55	2607	.04*
Late Measures										
total time	F_1	49.32	41434	.0001*	20.18	16076	.0001*	8.84	13344	.0004
	F_2	118	6449	.0001*	12	12	.0001*	6.79	6449	.003*
spillover	F_1	8	1412	.008*	1.18	1283	.315	1.24	1057	.3
	F_2	8.66	406	.006*	< 1			< 1		
regressions in	F_1	50.63	68	.000*	9.16	65	.000*	1.13	66	.33
	F_2	72	136	.000*	3.78	223	.03*	< 1		
regressions out	F_1	4.91	34	.034*	1.68	39	.19	< 1		
	F_2	6.04	78	.02*	< 1			< 1		

Note: Analyses are shown across participants (F_1) and items (F_2). For the transposition main effect the degrees of freedom were (1,31) for F_1 and (1,33) for F_2 . For all other effects, the degrees of freedom were (2,62) for F_1 and (2,33) for F_2

* $p < 0.5$

Table 5

Planned comparisons for each word type in each measure

	TL pseudo-root				TL existing-root				Simple			
	F	MSe	p		F	MSe	p		F	MSe	p	
Early Measures												
first fixation duration	F_1	9.94	1642	.0036*	<1				<1			
	F_2	14.39	457	.003*	<1				<1			
gaze duration	F_1	27.72	7222	.0001*	14.38	5280	.0006*	4.75	4810	.037*		
	F_2	34.71	2353	.001*	9.24	3103	.01*	3.81	2365	.077		
Late Measures												
total time	F_1	56.66	15011	.0001*	29.27	42087	.0001*	17.87	11024	.0002*		
	F_2	61.68	5317	.0001*	42.06	10616	.0001*	20.95	3415	.0008*		
spillover	F_1	<1			4.28	1266	.047*	8.63	939	.006*		
	F_2	<1			2.61	504	.13	11.11	241	.007*		
regressions in	F_1	34	37	.000*	23	66	.000*	23.97	31	.000*		
	F_2	27.02	44	.000*	26.45	54	.000*	18.78	37	.001*		
regressions out	F_1	5.01	19	.03*	1.56	38	.2	2.21	11	.14		
	F_2	1.67	54	.22	4.84	11.5	.05*	1.8	12	.21		

Note: Analyses are shown across participants (F_1) and items (F_2). For all word types the degrees of freedom were (1,31) for F_1 and (1,11) for F_2 .

* $p < 0.5$

Table 6

differences in the TL effect across word type

	TL pseudo-root vs. Simple				TL pseudo-root vs. TL existing-root				Simple vs. TL existing-root			
	F	MSe	P		F	MSe	P		F	MSe	P	
Early Measures												
first fixation duration	F_1	4.2	6793	.04*	3.59	7242	.067		< 1			
	F_2	6.33	5610	.017*	6.28	5561	.0173*		< 1			
gaze duration	F_1	7.59	23107	.01*	2.65	22338	.11		1.83	16888	.19	
	F_2	6.98	5213	.01*	2.6	5213	.12		1.06	5213	.3	
Late Measures												
Total time	F_1	11.3	40513	.002*	1.14	61843	.29		15.36	57774	.0005*	
	F_2	7.22	93155	.01*	<1				12.45	160577	.001*	
spillover	F_1	6.75	7499	.015*	3.4	10952	.075		< 1			
	F_2	2.24	3242	.144	1.71	2480	.199		< 1			

Note: Analyses are shown across participants (F_1) and items (F_2). For all word types the degrees of freedom were (1,31) for F_1 and (1,11) for F_2 .

* $p < 0.5$