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Words with and without internal structure: what determines the nature of orthographic and morphological processing?

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Abstract

Recent studies suggest that basic effects which are markers of visual word recognition in Indo-European languages cannot be obtained in Hebrew or in Arabic. Although Hebrew has an alphabetic writing system, just like English, French, or Spanish, a series of studies consistently suggested that simple form-orthographic priming, or letter-transposition priming are not found in Hebrew. In four experiments, we tested the hypothesis that this is due to the fact that Semitic words have an underlying structure that constrains the possible alignment of phonemes and their respective letters. The experiments contrasted typical Semitic words which are root-derived, with Hebrew words of non-Semitic origin, which are morphologically simple and resemble base words in European languages. Using RSVP, TL priming, and form-priming manipulations, we show that Hebrew readers process Hebrew words which are morphologically simple similar to the way they process English words. These words indeed reveal the typical form-priming and TL priming effects reported in European languages. In contrast, words with internal structure are processed differently, and require a different code for lexical access. We discuss the implications of these findings for current models of visual word recognition.

What determines lexical architecture in alphabetic orthographies? Fast and efficient recognition of words requires some form of organization so that the visual analysis of their constituent letters be mapped into lexical representation within minimal time. Most, if not all, models of visual word recognition assume, therefore, that the lexical architecture mimics the alphabetic principle, and that the processing system is tuned to the word's linear orthographic structure. Consider, for example, the Entry-Opening model (Forster & Davis, 1984; Forster, 1999). It assumes that lexical entries are organized into bins based on their orthographic form, so that words sharing similar letter sequences (or orthographic neighbours) are located in the same bin. Upon presentation of a printed word, the orthographic properties of the input are used to calculate an approximate address (i.e., a bin number), which considers the array of letters in the word. Alternatively, in various types of interactive activation models (e.g., IAM, McClelland & Rumelhart, 1981; the Multiple Read Out Model, Grainger & Jacobs, 1996; the Dual-Route-Cascaded model, Coltheart, Rastle, Perry, & Ziegler, 2001; or the Connectionist Dual Process models (CDP, and CDP+, Zorzi, Houghton, & Butterworth, 1998; Perry, Ziegler & Zorzi, 2007) letter identity and letter position of the input contributes one way or another to the amount of activation of top-level word units. Hence, the architecture of these models is structured so that relative excitation or

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inhibition of word units is determined by the extent of their orthographic overlap. Finally, attractor-based models of reading (e.g., Rueckl, 2002) assume that each printed word has a unique attractor in a perceptual space, which is structured, again, in terms of orthographic properties. Thus, words that overlap in their orthographic structure are close together in this perceptual space, where orthographic overlap is determined by the sequence of letters.

The empirical support for the claim that words are lexically organized or interconnected by a principle of letter-sequence similarity comes from several research paradigms, but was especially influenced by masked priming experiments, in which primes and targets have a similar orthographic structure (i.e. form-priming). In short exposure durations, if primes and targets have overlapping orthographic representations, any processing carried out on the prime could be used to locate the target, shortening its recognition either by saving some search time (e.g., the Bin model), or by increased activation (e.g., the IAM model). Form-priming with short exposure durations has been repeatedly demonstrated in numerous studies across many Indo-European languages, such as English (e.g., Davis & Lupker, 2006), French (Ferrand & Grainger, 1994), Dutch (Van Heuven, Dijkstra, Grainger & Schiefers, 2001), and Spanish (e.g. Perea & Rosa, 2000). In contrast, with longer exposure durations, the prime may be recognized, at least partially, and since orthographically similar word forms may compete with one another as part of the recognition process, the prime may suppress the processing of the target. In line with this argument, Chateau & Jared (2000) indeed reported strong effects of orthographic facilitation with a prime exposure of 30 msecs, but strong inhibition with a prime exposure of 60 msecs. The various models of visual word recognition also predict that the priming effect in lexical decision depends on factors such as prime-target relative frequency, the lexical status of the prime, or neighbourhood density. Regarding frequency, in general, stronger facilitation or inhibition is expected when the frequency of the prime exceeds that of the target (e.g., Segui & Grainger, 1990). As to the lexical status of the prime, nonword primes that are orthographically similar to the targets were found to produce stronger priming than words, since no prime-target competition is expected for nonword primes (e.g., Holyk & Pexman, 2004). Finally, strong facilitation is obtained for word targets having few orthographic neighbours and weak facilitation for words having many (e.g., Forster & Taft, 1994). This is because the prime predicts the target with greater efficiency when the orthographic neighbourhood includes few candidates than when it includes many (or from an activation point of view, this is due to competing activities of all the words sharing the same letters).

Considering letter position, in recent years, several studies have consistently reported robust masked-orthographic priming effects when primes and targets shared all of the same letters but in a slightly different order (e.g., *GADREN* priming *GARDEN*, Perea & Lupker, 2003a; Perea & Lupker 2004; Schoonbaert & Grainger, 2004; and see Grainger & van Heuven, 2003 for a discussion). Target facilitation by transposed-letter (TL) primes was reported in Indo-European languages such as English (e.g., Perea & Lupker, 2003a), French (Schoonbaert & Grainger, 2004), Spanish (Perea & Carreiras, 2006a), and even for non Indo-European languages such as Basque (Duñabeitia, Perea & Carreiras, 2007), and Japanese Katakana (Perea & Perez, 2009). Several studies conducted by Perea and his colleagues demonstrated that the locus of the effect is orthographic rather than phonological (Perea & Carreiras, 2006a; Perea & Carreiras, 2006b; Perea & Carreiras, 2008; Lupker, Perea, & Davis, 2008), and that transposition of two adjacent letters in the prime may also lead to significant semantic priming for related targets (*JUGDE* priming *COURT*; Perea & Lupker, 2003b). Recently, Guerrera & Forster (2008) have shown that masked form priming can be obtained even with extreme transpositions (*sdiwelak* priming *sidewalk*).

The finding that change of letter order nevertheless produces robust form-orthographic priming effects has brought about a new generation of models of visual word recognition which do not encode letter positions in rigid and absolute terms. For example, the SOLAR model (Davis, 1999) encodes letter position by the relative pattern of activities across letters in a word, so that the initial letter attains the highest activation and activation levels decrease along the letter-string. The SERIOL model (Whitney, 2001; Grainger & Whitney, 2004; Whitney, 2008) bases letter position coding on “open bigram” units, which do not contain precise information about letter contiguity, but preserve information regarding relative position. For example, *DS*, *EK*, and *DK* are bigram units of *DESK*, just like *DE*, *ES*, and *SK* are. In contrast, The Bayesian Reader model (e.g., Norris, 2006; Norris & Kinoshita, 2008; 2009) and The Overlap model (Gomez, Ratcliff & Perea, 2008) posit a noisy letter order scheme in which information regarding order of letters becomes available more slowly than information about letter identity (see Grainger, 2008, for a review). Recently, Norris, Kinoshita, & van Casteren (2010), have implemented noisy letter-position rather than letter-order, as part of their computational model. All of these models, however, share one implicit tenet. They assume that in all alphabetic orthographies the cognitive processing system, which encodes the orthographic input, treats all of the word’s letters within the word alike. Hence, apart from the initial and the final letters, which define the word boundaries, all letters contained in a given word are created equal for generating an orthographic code, and this holds for all languages where letters represent phonological units.

Recently, we have presented a series of findings from Hebrew that seems to challenge this tenet. Hebrew, like any Indo-European language, has an alphabetic orthography, which in this case consists of 22 letters (see Appendix A). The letters in a word mostly represent consonants, whereas vowels are mainly conveyed by diacritic markers ("points") added to the consonant. In most texts, however, aside from children's literature and holy scripts, the points are omitted. In addition, some vowels may also be represented by letters, depending on the orthographic or phonological context. The main difference between Hebrew and non-Semitic languages concerns its morphological structure. Most Hebrew words can be decomposed into two abstract morphemes: a root and a word-pattern. Roots in most cases consist of three consonants whereas word-patterns can be either a sequence of vowels or a sequence consisting of both vowels and consonants that contain “open” consonant slots, where the root consonants fit. This leads us to the most salient feature of Semitic languages’ morphology - roots and word-patterns are not appended to one another linearly, as in languages with linear morphology, such as English, French or Spanish. Rather, the consonants of the root are intertwined with the phonemes (and, therefore, the corresponding letters) of the word-pattern, as they are inserted into the empty consonantal slots. Unlike most base forms in English, roots and word-patterns are bound morphemes; hence, neither one can stand alone as an independent word and cannot be pronounced by itself. Only their combination results in a specific phonemic word-form with a specific meaning. The two basic morphemic units in Hebrew (the root and the word-pattern) differ in their linguistic characteristics. While word-patterns, at least in the nominal system, convey primarily vague grammatical information about word class (there are more than a hundred such patterns), the root carries the core meaning of the word. For example, the Hebrew word /tizkoret/ (“a memo”) is a derivation of the root z.k.r. This root is embedded into the consonant slots in the phonological word-pattern /tiCCoCet/ (each C indicates the position of a root consonant). The root z.k.r alludes to anything related to the concept of memory, and the phonological pattern /tiCCoCet/ is often (but not always) used to form feminine nouns. It is the merging of the root with the word-pattern that forms the word meaning “a memo”. Other phonological word-patterns may combine with the same root to form different words with different meanings that can be either closely or remotely related to the notion of memory (e.g., /zikaron/ (a memory), /mazkir/ (a secretary), /zxira/ (remembering), /hizkir/ (reminded), etc). What all of these words have in common are the three consonants, constituting the root morpheme z.k.r (Berman, 1978; Glinert, 1989).

Given the important role of the root morpheme in forming word structure as well as word meaning, our previous work on morphological processing in Hebrew explored the possibility that the root plays a significant role in lexical organization. Indeed, numerous experiments that examined visual word recognition in Hebrew showed that root primes facilitate both lexical decision and the naming of target words that are derived from these roots. These findings suggested that in the course of word recognition, words are decomposed into their constituent morphemes, and that the consonant letters constituting the root are the target of lexical search (e.g., Frost, Forster, & Deutsch, 1997; Frost, Deutsch, & Forster, 2000; Frost, Deutsch, Gilboa, Tannenbaum, & Marslen-Wilson, 2000). More relevant, however, is the impact of orthographic similarity on word recognition in Hebrew (Frost, Kugler, Deutsch, & Forster, 2005). In a set of eight experiments, we reported that in contrast to Indo-European languages, no form-orthographic priming could be obtained in Hebrew or in Arabic (also a Semitic language). Thus, orthographically similar prime-target pairs differing by one letter only, did not show any significant facilitation or inhibition in any experimental condition. Moreover, in sharp contrast to Indo-European languages, masked form-priming seemed unaffected by the lexical status of the prime, or by neighbourhood density. Of special interest in the present context were two experiments involving bilingual participants. In these two experiments, Hebrew L1--English L2 and English L1--Hebrew L2 bilinguals were presented with form-related primes and targets in Hebrew and in English. When tested in English, these bilingual speakers indeed demonstrated robust form-priming. However, in both experiments, no such effect was obtained when these same participants were tested with Hebrew material.

The interpretation of these findings was that Hebrew lexical space is organized in a radically different manner than that of English or other Indo-European languages. As previously discussed, in English, lexical space is defined according to orthographic dimensions, which specify the location of each word considering its constituent letters and some flexible coding of their position. In contrast, Hebrew lexical space is structured according to a morphological entity, the root. Thus, all words that contain the same root are clustered together, and the perceptual distance (or the interconnections) between two words containing different roots is uncorrelated with their overall orthographic similarity. For example, /ti**zk**o**r**et/ (a memo) and /ti**zm**o**r**et/ (an orchestra), are derived from the same word-pattern but from two different roots (**z**.**k**.**r** and **z**.**m**.**r**, respectively). These two derivations would have been considered "orthographic neighbours" in English lexical space, since they share all of their letters but one, but in Hebrew lexical space they would be located far apart because they are derived from different roots.

Important support for this claim comes from recent studies that examined the impact of letter transpositions in Hebrew and Arabic. Velan & Frost (2007) investigated reading performance of Hebrew-English bilinguals, using Rapid Serial Visual Presentation (RSVP). They presented Hebrew-English balanced bilinguals with sentences in English and in Hebrew, half of which had transposed-letter (TL) words, and half of which were intact. The sentences were displayed on the centre of the screen rapidly, word-by-word. Velan and Frost found a marked difference in the effect of letter-transposition in the two languages. For English materials, the report of words was virtually unaltered when sentences included words with transposed letters. Moreover, most participants were unaware of the transposition manipulation. In contrast, for Hebrew materials, the correct report of Hebrew words dropped dramatically in sentences containing transpositions, and detection of transposition was immediate. Velan and Frost argued that since lexical access in Hebrew is based on a preliminary search of the consonant letters of the root entry, and since different roots in Hebrew share the same three letters but in a different order, any transpositions that involve root letters would interfere with lexical access. Consequently, Hebrew readers have an increased sensitivity to letter transpositions relative to readers of Indo-European languages. These conclusions were further supported in a series of experiments that examined transposed-letter effects in a fast priming paradigm (Velan & Frost, 2009). This study demonstrated that, in contrast to English, French, or Spanish, transposed-letter (TL) nonword primes do not facilitate recognition of targets in Hebrew. More importantly, if the TL nonword primes include an existing root morpheme, they produce inhibition. These conclusions were supported by a recent study in Arabic, also a Semitic language, showing that the typical TL priming effect is not obtained in that language either (Perea, Abu Mallouh & Carreiras, 2010).

The results from Hebrew seem to provide an interesting challenge to current suggestions regarding the nature of orthographic coding. Hebrew is an alphabetic orthography like English, French, or Spanish, where letters represent phonemes. There is no a-priori reason why Hebrew would not be read like any Indo-European language by computing from the full letter-sequence, an orthographic code that mimics the alphabetic principle. Why, then, is Hebrew read differently? The present paper addresses this theoretical question.

Comparing Hebrew or Arabic to most other languages with alphabetic orthographies, the main difference seems to lie in the structure of base forms, or rather the lack of it. Base form is usually defined as the basic morpheme, usually an independent word, which constitutes the form to which derivational and inflectional morphemes are added (such as *drive-driver / drive-drives*). Most current computational models of visual word recognition are naturally constrained to the processing of base forms. Base forms in Indo-European languages consist of an arbitrary alignment of consonants and vowels, with few, usually phonotactic constraints, on this alignment. In this context, base forms in English, French, Dutch, or Spanish, have minimal internal structure, if any. Base forms in Hebrew, on the other hand, are highly structured. Most of them are bi-morphemic entities, having a root and a word-pattern as their constituent morphemes, morphemes that cannot stand on their own. The phonological word-patterns determine a set of conditional probabilities that predict whether a given consonant or vowel will follow the previous phoneme. Since the cognitive system is a statistical-structure detecting device (see Dishon-Berkovitz & Elgom, 2000), it picks up the implicit internal structure of Semitic words from the orthographic structures and this seems to govern the recognition process.

Given the arbitrary alignment of letters in Indo-European languages, all of the base form's letters are considered equivalent for generating an orthographic code for lexical search. This produces all current findings regarding form-priming and letter transposition effects. In contrast, in Semitic languages, the internal structure of the base form leads to fast morphological decomposition which determines an orthographic code that focuses on root letters, whose locations are systematically pre-determined by the word-patterns. This is why form-priming or letter-transposition effects are not obtained. According to this view, the modelling principles and the nature of the orthographic code in most current models of visual word recognition (see Grainger, 2008, for a review) reflect a critical feature of Indo-European languages: base forms have minimal internal structure. How could we test this theoretical assumption? The interpretation of any cross-linguistic investigation is bound to be equivocal since many factors may drive differential performance.

Hebrew, however, allows a direct test of this hypothesis. Although most base forms can be decomposed into a root and a word-pattern, Hebrew also has a large set of morphologically simple words that do not have the typical Semitic structure, and in that respect, they resemble Indo-European base words. Such words have infiltrated Hebrew throughout history from adjacent linguistic systems such as Hitite, Persian, Greek, etc., but are considered by native Hebrew speakers, who are unfamiliar with their historical origin, as entirely Hebrew. For example, the base word /agartal/ (printed as AGRTL, meaning "a vase") is not Semitic, since it cannot be decomposed into a root and a Semitic word-pattern.[i] /agartal/ infiltrated Hebrew in biblical times, and can be traced to either Old Persian or Hitite. Hebrew has a large set of such words -- often names of objects, fruits, vegetables, or plants, but not exclusively. More importantly, these words are prevalent, and some of them are highly-frequent.

In the following four experiments, we systematically investigated the processing of words like /agartal/ which do not have any internal structure, and are in that respect similar to base words in English. Similar to our studies with root-derived words, we monitored the impact of letter-transposition on reading, as well as effects of orthographic similarity for this type of Hebrew words. Specifically, we focused on the following empirical questions: are Semitic (i.e. morphologically complex) words, and “English-like” (i.e. morphologically simple) words processed alike by Hebrew readers? Is lexical organization for “English-like” Hebrew words similar to English or similar to Hebrew? In other words, would speakers of Hebrew impose the Hebrew processing principles or rather the English ones on "English-like" Hebrew words?

Experiment 1

Experiment 1 examined the impact of letter transpositions on reading Semitic, Hebrew non-Semitic, and English words. The procedure and design were similar to the original study of Velan & Frost (2007), and monitored performance of Hebrew-English bilinguals in Rapid Serial Visual Presentation (RSVP). The Hebrew target words in the original Velan & Frost (2007) study were all root-derived (i.e., morphologically complex), and the results indicated that transpositions had little effect with English material, whereas they had a dramatic effect with Hebrew materials. The aim of Experiment 1 was, therefore, twofold: first, to replicate the cross-linguistic differences regarding the impact of letter transposition in English and in Hebrew; second, to contrast root-derived and morphologically simple Hebrew words and examine whether letter transposition effects for morphologically simple words resemble the effects obtained with morphologically complex Hebrew words, or are more in line with reading English words. If all Hebrew words are processed alike, then letter transpositions of *both* morphologically simple and morphologically complex Hebrew words would result in a similar and detrimental effect on reading. If, however, lexical organization and orthographic processing is governed by the internal structure of the printed words, then the impact of transposing letters on reading morphologically simple Hebrew words would be similar to its impact on reading English words.

Method

Participants—The participants were 18 students at the Hebrew University, who were all Hebrew-English balanced bilinguals (both English and Hebrew are spoken at home). Subjects’ proficiency in English and in Hebrew was verified through self-report in a questionnaire that assessed their level in speaking, writing and reading in both languages.

Stimuli and Design—The stimuli consisted of 60 sentences, 7–11 words long, and in each sentence two target words were embedded. The 60 sentences were divided into three experimental conditions: (1) 20 Hebrew sentences with target words like /agartal/ which are morphologically simple (2) 20 Hebrew sentences with target words like /tizkoret/ which are root-derived (3) 20 English sentences. Target words in each sentence were either presented intact or had letter transpositions, so that each participant saw 30 intact sentences and 30

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[i] Morphological complexity for these words is obtained only through inflectional suffixation such as plural (e.g., /agartal/ - /agartalim/) as in Indo-European languages.

sentences with transpositions. The two target words within a given sentence were never consecutive and never appeared at the beginning or at the end of the sentence. In addition, sentences were constructed in a way that target words could not be predicted by the semantic context. The sentences for Experiment 1 as well as all stimuli employed in the following experiments are available at the following website: http://atar.mscc.huji.ac.il/~frost/files/Stimuli.TL_VF.internal.pdf.

Clearly, as in any cross-linguistic study, there are inherent problems in equating stimuli, given the idiosyncratic structural properties of the investigated materials. For example, function words are independent words in English, while they are clitics in Hebrew, and words in Hebrew are on average shorter than in English, as some of the vowel information is not represented in print. Such differences cannot be avoided. However, similar to Velan & Frost (2007), we focused on factors that have been demonstrated to affect letter transposition effects. These mainly involve the identity and position of transposed letters. We therefore matched the letter transposition criteria in the three materials as follows: given the relative importance of initial and final letters (e.g., Rayner, White, Johnson & Liversedge, 2006), in both languages, transpositions only involved internal letters. Due to the difference in transposing vowels in comparison with consonants (Perea & Lupker, 2004), in all the materials only consonants were transposed. All transpositions involved two adjacent consonants. To avoid any confound with lexicality, for both English and Hebrew materials, letter transpositions resulted in nonwords only. Thus, in Hebrew morphologically complex words, the letters of the root were transposed, creating a non-existing root, and then re-embedded in the original word-pattern creating the nonword. Target words were at least 5 letters long, with an average of 6.3 letters for English and 5.3 and 5.6 letters for the morphologically simple and the morphologically complex Hebrew words, respectively. In addition, target words had similar frequencies in all the materials (23.8 per million for English, and 17.6 and 20.1 per million for the morphologically simple and the morphologically complex Hebrew words, respectively). Finally, in all the materials, we employed target words with similar neighbourhood density to aim for an identical number of competing orthographic neighbours (mean of 4.1 for English[ii] words and 4.2 and 5.3 for the morphologically simple and morphologically complex Hebrew words respectively, F<1.0).

Two experimental lists were constructed, each list contained ten intact sentences and ten transposed sentences in each experimental material. Sentences that were intact in List A were transposed in List B, and vice versa. All sentences in a given language were presented in one block; a third of the participants were first tested with the Hebrew morphologically simple material, another third first tested with the Hebrew root-derived material, while the remaining third viewed the English material first.

Procedure and Apparatus—The software used for presentation of stimuli and for measuring the reaction times was the DMDX display system (Forster & Forster, 2003). The procedure was identical in both the Hebrew and the English blocks. The experimenter pressed the space bar to initiate the sentence presentation. Each sentence was then presented word-by-word, each word appeared on the centre of the screen for 200 msec. Subjects were informed ahead of time that some sentences may involve letter transposition. Nonetheless, they were asked to produce all sentences without replicating the actual transpositions if they were perceived. Following the final word of each sentence, participants repeated the sequence of words that they had perceived. The dependent measure was how often participants produced the correct words in English and in Hebrew from the transposed version, relative to the intact version.

[ii] English frequency and neighbourhood density data were taken from Medler & Binder, 2005. Hebrew frequency data was taken from Frost & Plaut, 2005.

Results and Discussion

For each participant, we calculated the overall percentage of correct report of all the words in the sentence, and correct report of target words only, in intact sentences and in the sentences containing transpositions. The results are presented in Figure 1.

As can be seen in Figure 1a, participants' baseline performance in reading the full word sequence in the sentences was high and very similar across the three target conditions: ninety-two percent of all words were reported correctly in both the English and the Hebrew morphologically simple materials, and 91% of all words were reported correctly in the Hebrew sentences with morphologically complex words. This outcome confirms that for our balanced bilinguals, the materials employed in all three conditions were indeed very similar in terms of reading complexity. Turning to the impact of letter-transposition, it affected reading very differently in the three experimental conditions. In English, not surprisingly, transpositions had little effect, and correct reading under normal (92%) and transposed-letter presentation (88%) was quite similar. In contrast, a dramatic effect was observed with the Hebrew root-derived words, where performance in sentences that included words with transposed letters dropped from 91% to 78%. These results provide a full replication of the Velan & Frost (2007) study.

The interesting result, however, concerns the effects obtained for the Hebrew morphologically simple materials. The findings are straightforward: reading performance in the Hebrew sentences containing morphologically simple target words was identical to that of English sentences (92% and 88% under normal and transposed presentation, respectively), that is, transpositions had little effect on word reading. A two-way ANOVA with the main factors of target type (English, Hebrew morphologically simple, Hebrew root-derived) and transposition (intact vs. transposed text) revealed this interaction to be highly significant ($F(2,34) = 24.37$, MSE = 12, $P < .0001$), as did each of the main factors: ($F(2,34) = 6.24$, MSE = 3, $P < .005$) for target type, and ($F(1,17) = 30.61$, MSE = 41, $P < .0001$) for the transposition factor.

Considering the target words only, we observe a very similar pattern to the whole sentence reading. In English, transpositions had a small effect on target perception, and correct recognition dropped from 89% in the intact text to 82% in the transposed text. In contrast, transpositions affected the recognition of Hebrew root-derived target words quite dramatically, and correct reading in the intact text deteriorated from 89% to 68% in the transposed text, again, replicating Velan & Frost's (2007) results. The Hebrew morphologically simple targets were affected by letter transpositions only slightly, similar to the English words, (90% correct identification with intact text and 85% in the transposed text). A two-way ANOVA revealed this interaction to be highly significant in both participants and items ($F_1(2,34) = 18.39$, MSE = 36, $P < .0001$; $F_2(2,57) = 7.17$, MSE = 101, $P < .0002$). The main effect of target material was significant for participants but not for items ($F_1(2,34) = 13.27$, MSE = 59, $P < .0001$; $F_2(2,57) = 2.28$, MSE = 363, $P < .111$), and the main effect of transposition was significant for both participants and items ($F_1(1,17) = 52.86$, MSE = 58, $P < .0001$; $F_2(1,57) = 34.21$, MSE = 101, $P < .0001$).

The results of Experiment 1 replicate Velan & Frost's (2007) findings, indicating that Hebrew root-derived words and English words are indeed processed differently. More importantly, the results for the Hebrew morphologically simple words suggest that readers of Hebrew process such words just as they process English words. Hence, it seems that, indeed, what determines the effect of letter transpositions is whether the printed words have or do not have an internal structure. Experiment 1 suggests that the readers of Hebrew display a striking flexibility in that they seem to process and organize root-derived and morphologically-simple words quite differently. The difference in performance with the two types of Hebrew materials does not stem from superficial orthographic structure or from factors such as frequency or neighbourhood density, but from morphological complexity. Experiment 2 was designed to further explore this possibility.

Experiment 2

In experiment 2, we extended our investigation to examine TL priming effects. In a recent study, Velan & Frost (2009) argued that TL priming effects are not universal, and demonstrated that whereas in English, French, or Spanish nonword primes like *judge* speed lexical decisions for target words like *jugde*, in Hebrew, TL primes do not have any facilitatory effect on their respective target recognition. Since all words in the Velan & Frost (2009) study were naturally the typical Semitic root-derived words, the aim of Experiment 2 was to examine whether TL priming effects can be obtained with Hebrew morphologically simple words, just as they can be obtained with any Indo-European language. To expand the scope of our investigation, we included in the experiment another type of Hebrew words which are not root-derived.

Some words in Hebrew are Semitic as they are derived from a Semitic word-pattern; however, they include a tri-consonantal structure which is a pseudo-root (see Feldman, Frost, & Pnini, 1995). Consider for example a word like /tarmil/, “a backpack”. This word is composed of the Hebrew word-pattern, taCCiC (such as /taklit/, “a record”, /targil/, “an exercise”, or /tarxiS/ “a scenario”). However, in contrast to these three examples, where k.l.t, r.g.l, and r.x.S are productive roots (e.g., /klita/, /hirgil/, /raxaS/, etc.), the tri-consonantal structure r.m.l. in /tarmil/ is non-productive, meaningless, and does not appear as a sequence in any other root-derived Hebrew word. Words like /tarmil/ have then some structure, in the sense that they are constructed by a word-pattern morpheme, but on the other hand, they cannot be decomposed into a meaningful and productive root. Similar to the morphologically simple words, they are quite prevalent. In Experiment 2, we thus examined TL priming effects with three types of words: root-derived words such as in the Velan & Frost (2009) study, Semitic words like /tarmil/ that do not contain a meaningful and productive root, and words like /agartal/ that are morphologically simple. We were intrigued to see whether TL priming effects would be revealed for either words like /tarmil/ or / agartal /, as they are obtained in English, French, or Spanish.

Method

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

Stimuli and Design—The stimuli consisted of 72 target words. All targets were nouns, four to six letters long, and contained two to four syllables, with four to eight phonemes. Their mean number of letters was 4.6 and their mean number of phonemes was 6.18. The mean word frequency per one million words was 5.17, range: 1–32, and the mean neighbourhood density was 3.3, range 1–14. The target words consisted of three types of Hebrew words: 1) 24 morphologically simple words like /agartal /, 2) 24 Semitic words with a non-productive root like /tarmil/, and 3) 24 root-derived words with the standard Semitic structure of root and words-pattern such as /tizkoret/.

Each type of target word was paired with three primes to create three experimental conditions: (a) an Identity condition - primes were identical to the target words, (b) the TL condition - primes consisted of the transposed letters of the target, which formed a nonword (in both the non-productive root and the root-derived materials two letters from the root were transposed creating a pseudo-root), (c) a control condition in which one of the transposed letters was replaced. Note, that all primes of the non-productive root and the root-derived materials were derived from the same word-pattern as the target. An example of the stimuli used in the experiment is presented in Table 1.

When selecting the stimuli, we had significant constraints. First, given the well-documented impact of transposing the initial word-letter (e.g. Guerrera & Forster, 2008), the first letter of all of our target words could not be a root letter but rather a word-pattern letter. Second, given the demonstration in English, Spanish and Basque that TL effects are significantly reduced if morphemic boundaries are crossed (Christianson, Johnson, & Rayner, 2005; Duñabeitia, Perea & Carreiras, 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. The three types of words were matched in terms of length, frequency, number of syllables and neighbourhood density.

The nonwords consisted of 72 pseudo-nouns: 24 of which were a legal sequence of letters to match the morphologically-simple target words, and the rest were derived from existing word-patterns and tri-consonantal sequences of non-existing roots. Like the words, nonword targets were four to six letters long and contained five to eight phonemes. Their mean number of letters was 4.6 and their mean number of phonemes was 6.1. Similar to the word targets, the nonwords were also divided into three experimental conditions: Identity, TL and control. The stimuli were divided into three lists. Each list contained 8 words and 8 nonwords in each of the nine (three types of words × three priming conditions) experimental conditions. We were concerned with the small number of items per experimental condition. However, we were restricted to a relatively small number of target words because we had to match the three experimental word types in length, frequency and neighbourhood density. The stimuli were rotated within the experimental conditions in each list in a Latin square design. Twenty-four different participants were tested in each list. This procedure allowed each participant to provide data points in each condition while avoiding stimulus repetition effects.

Procedure and Apparatus—The software used for presentation of stimuli and for measuring the reaction times was the DMDX display system (Forster & Forster, 2003). Each trial consisted of three visual events. The first was a forward mask consisting of a row of seven hash marks, which appeared for 500 msec. The mask was immediately followed by the prime, with exposure duration of 40 msec. The prime was immediately followed by the target word, which remained on the screen until the participant's response. The time lag between the participant’s response and the next stimuli was 1000 msec. All visual stimuli were centred in the viewing screen and were superimposed on the preceding stimuli. The procedures regarding print, font, prime-target separation, etc., follow all previous studies that used masked priming in Hebrew (see Velan & Frost, 2009, for a detailed description).

Results and Discussion

Response latencies were averaged for correct responses in each of the experimental conditions across participants and across items. For each participant, RTs that were outside a range of 2 SD from the participant’s mean were curtailed. Establishing cutoffs of 2 SDs above and below the mean for each participant minimized the effect of outliers. Any RT exceeding these cutoffs was replaced by the appropriate cutoff value. Trials on which an error occurred were discarded. This procedure was repeated in all of the following experiments.

For each word type, the effects of the identity and TL primes were assessed relative to the control baseline. The results are presented in Table 2. Lexical decisions for targets were facilitated in the identity condition where the primes were identical (+38, +51, +32 msec for the morphologically simple, non-productive and root-derived words, respectively). The more interesting result, however, concerns the TL priming effects. When primes consisted of letter transpositions, lexical decisions for targets exhibited a different trend for each of the word types. For root-derived targets, TL primes slightly inhibited (−3 msec) target recognition. These results replicate Velan & Frost's (2009) findings reporting no TL priming effects when the transpositions of root-letters created a nonsense root. Our main concern, however, were English-like words such as /agartal/, or words like /tarmil/ which do not contain a productive root. In contrast to the root-derived words, TL primes facilitated the recognition of the morphologically simple targets by +20 msec, and of the non-productive targets by +8 msec.

The results were subjected to a three-way ANOVA in which word type was one factor (morphologically simple, non-productive, root-derived) and the prime condition (identity, TL, control) was another. The third factor, word list, was introduced throughout the study merely to extract any variance due to list counterbalancing. We will therefore not report it.

The overall ANOVA revealed a significant main effect of prime condition across participants (F_1) and items (F_2), for response latencies, $F_1(2,138) = 102.68$, $MSE = 776$, $p < .0001$; $F_2(2,42) = 103.72$, $MSE = 314$, $p < 0.001$; as well as for errors, $F_1(2,138) = 29.86$, $MSE = 78$, $p < .0001$; $F_2(2,42) = 20.85$, $MSE = 37$, $p < .001$). The main effect of word type was significant in the participant analysis, but not in the item analysis, $F_1(2,138) = 11.77$, $MSE = 779$, $p < .0001$; $F_2(2,21) = 1.67$, $MSE = 2334$, $p < .213$; a similar pattern of results was exhibited by the error rates $F_1(2,138) = 6.85$, $MSE = 74$, $p < .001$; $F_2 < 1$. More importantly, however, the interaction of prime condition and word type was significant for both participants and items, $F_1(4,276) = 3.84$, $MSE = 816$, $p < .005$; $F_2(4,42) = 5.21$, $MSE = 314$, $p < .002$; as well as for errors, $F_1(4,276) = 4.05$, $MSE = 79$, $p < .003$; $F_2(4,42) = 2.87$, $MSE = 37$, $p < .03$. Thus, facilitation in the experiment was modulated by word type.

We now turn to a series of planned comparisons examining the TL effect, which are the focus of the experiment. In the root-derived word type, the slight inhibitory effect caused by the transpositions (−3 msec) was not significant for both participants and item analyses, F_1 & $F_2 < 1$. The +20 msec TL priming effect for the morphologically simple words was significant in both the participant and the item analysis F_1 (1,69) = 14.14, $MSE = 633$, $p < .0001$; $F_2(1,7) = 17.72$, $MSE = 283$, $p < .004$. As to the non-productive-root words, the +8 msec facilitation was not significant for both participants and items, $F_1(1,69) = 1.41$, $MSE = 1011$, $p < 0.24$; F_2 (1,7) = 1.95, $MSE = 458$, $p < .21$. The nonwords did not reveal any effect of prime condition (F_1 &F_2 <1). This finding is in accordance with previous masked priming results in Hebrew, confirming that the priming effect is mainly lexical.

The results of Experiment 2 converge with those of Experiment 1. Morphologically simple Hebrew words with no internal structure reveal the well-established TL priming effect obtained in Indo-European languages. These words contrast with the typical Hebrew root-derived words, for which TL priming cannot be obtained. Since priming was monitored with very brief exposure duration, these results suggest that the Hebrew readers' sensitivity to the word's internal structure can be revealed at the very early stages of visual word recognition.

Whereas the findings for morphologically simple, and root derived words seem straightforward, no clear verdict emerges regarding words derived from a Semitic word-pattern with a non-productive root. Whether the non-significant facilitation obtained for these words reflects a weak effect, or whether words such as /tarmil/ are processed and considered by Hebrew readers as typical Semitic root-derived words, requires further investigation.

Experiment 3

As the results regarding the non-productive target words were inconclusive, the aim of Experiment 3 was to replicate the results of Experiment 2 for the Hebrew morphologically simple and non-productive target words, and to further explore their processing when contrasted with root-derived words. Recall that in Experiment 2, two of the consonants of the root were transposed creating a nonsense root embedded in the prime. In Experiment 3, the transposition of two of the root consonants created an existing root, but nonetheless, when the transposed root was embedded in the target's word-pattern it still created a nonword prime. Similar to Velan & Frost (2009), we expected this manipulation to create a significant inhibition, which contrasts with the typical facilitation obtained in other alphabetic orthographies.

Method

Participants—Sixty-six students from the Hebrew University participated in the experiment for course credit or for payment. All participants had either normal or corrected to normal vision and were native speakers of Hebrew.

Stimuli and Design—The stimuli consisted of 90 target words. All targets were nouns, four to six letters long, and contained two to four syllables, with four to eight phonemes. Their mean number of letters was 4.6 and their mean number of phonemes was 6.28. The mean word frequency per one million words was 4.59, range: 1–32, and the mean neighbourhood density was 3.7, range 1–14. Similar to Experiment 2, target words consisted of three types of Hebrew words: 1) 30 morphologically simple words like /agartal/, 2) 30 Semitic words with a non-productive root like /tarmil/, and 3) 30 Root-derived words with the standard Semitic structure of root and word-pattern such as /tizkoret/.

Each type of target word was paired with three primes to create three experimental conditions: (a) an Identity condition - primes were identical to the target word, (b) the TL condition - primes consisted of the transposed letters of the target, which formed a nonword. For the non-productive root, two consonants of the root were transposed creating a pseudo-root. However, in contrast to the previous experiment, for the root-derived targets, transposition of the two consonants of the root created a consonantal sequence that represents an existing meaningful root, yet the letter string was a nonword), (c) a control condition in which one of the transposed letters was replaced. Note, that all primes of the non-productive root and the root-derived materials were derived from the same word-pattern as the target. The nonwords consisted of 90 pseudo-nouns, created in a similar manner as the nonwords in Experiment 2. Like the words, nonword targets were four to six letters long and contained five to nine phonemes. Their mean number of letters was 4.6 and their mean number of phonemes was 6.3. Similar to the word targets, the nonwords were also divided into three experimental conditions: Identity, TL and control.

The stimuli were divided into three lists. Each list contained 10 words and 10 nonwords in each of the nine (three types of words × three priming conditions) experimental conditions. The stimuli were rotated within the experimental conditions in each list in a Latin square design. Twenty-two different participants were tested in each list. The procedure and apparatus were identical to those employed in the previous experiment.

Results and Discussion

Response latencies were averaged for correct responses in each of the experimental conditions across participants and across items. Six stimuli were extracted from the analysis because of high error rates across all three conditions. In each word type, the effects of the

Identity and TL primes were assessed relative to the control baseline. The results are presented in Table 3. Lexical decisions for targets were facilitated in the Identity condition where the primes were identical (+26, +50, +52 msec for the morphologically simple, non-productive and root-derived words, respectively). As in Experiment 2, when primes consisted of letter transpositions, lexical decisions for targets exhibited a different trend for each of the word types. For root-derived targets, TL primes inhibited (−16 msec) target recognition. In contrast, transposition in the morphologically simple material and the non-productive root yielded a facilitation of +15 and +11 msec, respectively.

The results were subjected to a three-way ANOVA in which word type was one factor (morphologically simple, non-productive, root-derived) and the prime condition (Identity, TL, control) was another.

The overall ANOVA revealed a significant main effect of prime condition across participants (F_1) and items (F_2), for response latencies, $F_1(2,126) = 55.84$, $MSE = 1704$, $p < .0001$; $F_2(2,150) = 49.39$, $MSE = 918$, $p < .0001$; as well as for errors, $F_1(2,126) = 17.78$, $MSE = 52$, $p < .0001$; $F_2(2, 150) = 14.79$, $MSE = 26$, $p < .0001$. The main effect of word type was significant in the participant and item analyses, $F_1(2,126) = 41.55$, $MSE = 1792$, $p < .0001$; $F_2(2,75) = 8.75$, $MSE = 3797$, $p < .0004$; error analysis of word type yielded significance in participant but not in item analysis $F_1(2,126) = 9.54$, $MSE = 42$, $p < .001$; $F_2(2,75) = 2.57$, $MSE = 65$, $p < .08$. More importantly, however, the interaction of prime condition and word type was significant for both participants and items, $F_1(4,252) = 9.66$, $MSE = 1345$, $p < .0001$; $F_2(4,150) = 6.71$, $MSE = 918$, $p < .0001$. Error analysis was not significant for both participant and item analysis, $F_1(4,252) = 1.59$, $MSE = 38$, $p < .18$; $F_2 < 1$. Thus, facilitation in the experiment was again modulated by word type.

We now turn to the planned comparisons that examined the TL effects. In the root-derived word type, the observed inhibitory effect (−16 msec) was significant in participants and marginally significant for items , F_1 $(1,63) = 4.7$, $MSE = 1767$, $p < .034$; $F_2(1,25) = 3.29$, $MSE = 2335$, $p < .08$. The +15 msec TL priming effect for the morphologically simple words was significant in both the participant and the item analysis F_1 $(1,63) = 4.45$, $MSE = 1051$, $p < .039$; $F_2(1,25) = 4.78$, $MSE = 1130$, $p < .04$. As to the non-productive root words, the +11 msec facilitation did not reach significance for both participants and items, $F_1(1,63) = 2.64$, $MSE = 1252$, $p < .11$; F_2 $(1,25) = 2.23$, $MSE = 1801$, $p < .15$. As in experiment 2, there was no effect of prime condition for the nonwords ($F_1(2,126) = 1.71$, $MSE = 486$, $p < .19$; $F_2(2,58) = 1.3$, $MSE = 968$, $p < .281$).

The results of Experiment 3 demonstrate again the difference between processing words with and without internal structure. Letter-transpositions hindered recognition of the typical Semitic words that have a root. Hebrew then seems to be the only language where inhibition rather than facilitation occurs with TL primes, if the transposed letters represent a root different than that of the target. This outcome converges with Velan & Frost’s (2009) conclusions. Inhibition, however, turns into facilitation for “English-like” words with no internal structure. Hebrew native speakers treat these words like Indo-European readers do, and the well-established TL priming effects are obtained for these Hebrew words just as they are obtained in any other language. The non-productive words still remain a puzzle. TL priming effects for these words are elusive, and not as robust. The error variance for these stimuli was somehow larger than for the others. This points to a possibility that perhaps some of these words were processed as “English-like” words, whereas some were processed as Semitic words. We will further elaborate on this possibility in the General Discussion.

Experiment 4

To conclude our investigation, in experiment 4, we examined whether simple form-priming can be obtained with non-Semitic words. Frost et al. (2005) found that although form-priming is a robust effect in all Indo-European languages, facilitation due to orthographic similarity between prime and target cannot be obtained with Hebrew words. Although this study comprised one experiment, that involved non-productive words, these words were not systematically divided into morphologically simple words and words having a Semitic pattern. Moreover, the primes in Frost et al. (2005) were all words that consisted of existing neighbours of the targets. In Experiment 4, we employed nonword primes, aiming to investigate whether internal structure constrains form-priming effects, so that these can be revealed only for Hebrew words which resemble base-words in English.

Method

Participants—Sixty-nine students from the Hebrew University participated in the experiment for course credit or for payment. All participants were native speakers of Hebrew with normal or corrected to normal vision.

Stimuli and Design—The stimuli consisted of the 72 target words employed in Experiment 2: 24 root-derived words, 24 morphologically simple words, and 24 Semitic words with nonproductive roots. Each type of target word was paired with three primes to create three experimental conditions: (a) an Identity condition - primes were identical to the target word, (b) the form-related condition – nonword primes consisting of all the letters of the target but one. The location of the replaced letter varied across the words (c) a control condition – nonword primes differing from the target in all of their letters. The form primes were created in a similar manner to the control condition in experiments 2 and 3. Hence, only internal letters were replaced, and in the root-derived condition we replaced one of the root letters. The position of the replaced letter was mostly the 2nd or 3rd letter (31 and 32 times respectively), and the average position was 2.72. An example of the stimuli used in the experiment is presented in Table 4.

The stimuli were divided into three lists, and each list contained 8 words and 8 nonwords in each of the nine (three types of words × three priming conditions) experimental conditions. The stimuli were rotated within the experimental conditions in each list in a Latin square design. Twenty-three different participants were tested in each list. The procedure and apparatus were identical to those employed in the previous experiment.

Results and Discussion

Response latencies were averaged for correct responses in each of the experimental conditions across participants and across items. Seven stimuli were extracted from the analysis because of high error rates across all three conditions. In each word type, the effects of the identity and form primes were assessed relative to the control baseline. The results are presented in Table 5. Lexical decisions for targets were facilitated in the Identity condition where the primes were identical (+49, +49, +41 msec for the morphologically simple, non-productive and root-derived words, respectively). The more interesting result, however, concerns the form-priming effects. For root-derived targets, form-primes had a small and insignificant facilitation of (+6 msec). This is the exact mean facilitation across all experiments reported by Frost et al. (2005) with the typical root-derived Hebrew words. In contrast to the root-derived words, form primes facilitated the recognition of the morphologically simple targets by +13 msec, and the non-productive targets by +11 msec.

Since the main focus of our experiment was the possible interaction of form-priming and word type, we conducted a three-way ANOVA in which word type was one factor (morphologically simple, non-productive, root-derived), list another, and the prime condition included the form-related and the unrelated controls without the identity condition which was similar for all word types. ANOVA revealed that the main factors of word type and prime conditions were not significant F1 & F2<1 for both factors for both RT and errors. More importantly, the interaction between the word type and prime condition was highly significant for participants but not for items F_1 (2,132) = 9.18, *MSE* = 802, $p < .0001$; $F_2 < 1$. The weak item analysis probably reflects the small number of data points per subject in each condition given the loss of stimuli extracted from the analysis because of high error rates.

To examine the significance of individual priming effects we conducted a series of planned comparisons. These comparisons revealed that the small facilitation for root-derived words (+6 msec) was not significant for both participants and items, F_1 (1,66) = 1.34, *MSE* = 816, $p < .26$; F_2(1,20) = 1.31, *MSE* = 542, $p < .27$. In contrast, the +13 msec form-priming effect for the morphologically simple words was significant in both the participant and the item analysis F_1 (1,66) = 7.35, *MSE* = 782, $p < .008$; F_2(1,18) = 5.33, *MSE* = 965, $p < .03$. As to the non-productive-root words, the +11 msec facilitation was significant for participants but not for items, F_1(1,66) = 5.07, *MSE* = 882, $p < .028$; F_2 (1,18) = 2.57, *MSE* = 772, $p < .126$. For the nonwords, responses in the control condition were somewhat slower in the identity and form-related condition. This difference was significant (F_1(2,132) = 16.61, *MSE* = 366, $p < .0001$; F_2(2,46) = 17.91, *MSE* = 404, $p < .0001$) . However, since the priming obtained in the Identity condition was smaller than in the form-related condition, we believe this outcome to be an outlier.

Experiment 4 demonstrates that form-priming can be obtained in Hebrew, as long as the words do not have a Semitic structure, which includes a root morpheme. These findings then provide an important contrast to the Frost et al., 2005 study that showed that orthographic overlap between primes and targets does not facilitate target recognition in Hebrew. Note that the form priming effect obtained for “English-like” words such as /agartal/ was identical in size to the typical masked morphological priming effects consistently reported for root derivations (e.g., Frost et al., 1997).

General Discussion

In the present study, we conducted four experiments to explore the rules that govern visual word recognition in Hebrew. Our investigation employed RSVP as well as masked priming. These research paradigms tap the early phases of visual word recognition, and provide evidence regarding the access code for lexical search as well as the principles of lexical organization. Throughout the study, we contrasted the processing of Hebrew words which have a Semitic structure and consist of root derivations, with Hebrew words that resemble base-words in Indo-European languages and have no internal structure. Our investigation also included words that have Semitic properties and are derived from a known Hebrew word-pattern, but do not contain a productive root. The experiments focused on well-established cognitive markers of reading in alphabetic orthographies: in Experiment 1, we examined sensitivity to letter-transposition is sentence reading, in Experiments 2 and 3 we monitored TL priming effects, and in Experiment 4, we focused on form-priming.

Our findings were straightforward and unequivocal: words with and without internal structure are processed quite differently. The four experiments suggest that Hebrew readers display an amazing flexibility and seem to entertain in parallel two lexical systems. Words which are structured by intertwining a word-pattern with a tri-consonantal root do not reveal the typical form-priming or the well-established TL priming effects which have been demonstrated in a large variety of European languages. Moreover, the reading of these words is severely hindered by any transposition that disrupts the order of the root letters. These findings suggest that root-derived words are lexically organized by neighbourhoods of root morphemes, and not by encoding their full orthographic cluster. The registering of these root morphemes for lexical search involves rigid slot coding (see Velan & Frost, 2007, for a discussion). In contrast, Hebrew words that are morphologically simple, do not contain a root, and do not have any internal structure, are lexically organized by orthographic neighbourhoods just like base words in English. The processing of such words mimics other alphabetic orthographies, and generates an orthographic code in which all letters have equal status. These words reveal the typical form-priming and TL priming effects, and their reading in not affected by transpositions.

Aside from mapping the cognitive processes involved in reading Hebrew, the present findings address a fundamental question relevant to all models of visual word recognition. What determines lexical structure, and, subsequently, the properties of orthographic coding in alphabetic orthographies? Our starting point for this discussion is that theoretically the Hebrew orthographic lexicon could be structured like any European language, and the consequent reading process would follow identical principles with reasonable success. By this logic, the grain-size of computed units would then simply reflect the depth of the Hebrew orthography, just as in English, French, or Spanish (Frost, Katz & Bentin, 1987; Ziegler & Goswami, 2005), and lexical search would involve an orthographic or a phonological code that considers all of the word’s letters. The data from Hebrew do not seem to fit this possibility. The typical markers of reading in European orthographies are not revealed for Semitic Hebrew words, and they only emerge for “English-like” Hebrew words that are not derived from roots (see Frost, 2006, for a discussion).

In this context, “internal structure” (or rather the lack of it) does not merely reflect whether words are morphologically complex or morphologically simple. Rather, morphological complexity is correlated with important constraints on the possible alignment of phonemes. A word like /agartal/ for example, could have been /argatal/, /garatal/, /agratla/, or many other combinations of vowels and consonants, as there are no a-priori restrictions on its phonemic sequence. This is what characterizes base forms in European languages, where mostly phonotactic constraints determine the structure of phonemic clusters that have a meaning (e.g., non-permissible consonantal sequences such as KP in English, statistics of phonetic structure, such as CVCV sequences in Japanese, etc.). Since the orthographic system is designed to represent the spoken words of the language, consequently, there are few constraints on the identity of letters in a given slot of a printed word. Semitic languages such as Hebrew are constructed very differently. Most words have a structure that determines a family of permissible alignments of consonants and vowels. As previously described, all words having the structure /tiCCoCet/, for example, will begin with /ti/, end with /et/, the vowel co-articulated with the mid consonant would be /o/ etc. Hence, the initial syllable /ti/ determines with high probability that the following phoneme is the initial root consonant, etc. The excessive productivity of roots and the well-defined semantic field common to their derivations creates the high saliency of the root morpheme. Although speculative, this provides an interesting insight into why Indo-European languages “develop” an insensitivity to letter transpositions, whereas Hebrew readers are severely hindered by them. When there are few constraints on word structure and on the possible alignment of phonemes and letters, for simple combinatorial and probabilistic considerations there are few words that share the same subset of letters. Hence, word pairs like *calm-clam, lion-loin*, are relatively scarce. This is indeed the case in Indo-European languages. This type of linguistic environment can naturally allow noisy letter position coding. Hence, a transposed-letter word such as *JUGDE* can be easily recognised since there are no word competitors that share the same set of letters. Semitic Hebrew words, on the other hand, have an internal structure with a well-defined set of conditioned probabilities that rigidly determine few open slots for the consonants of the root only. Since most roots consist of three consonants, many words share the same subset of letters but with differences in letter order. Such a linguistic environment cannot allow for noisy letter position coding. Indeed, Friedmann and her colleagues have shown that letter-position dyslexia (LPD) can be easily diagnosed in Hebrew and not in English, because in contrast to English, errors in letter position in Hebrew most probability result in an existing word (Friedmann & Gvion, 2001; Friedmann & Gvion 2005). Our research from Hebrew shows that this internal structure is not only “picked-up” by the cognitive system, but it also results in organizational principles that allow the Hebrew reader optimal performance in his/her linguistic environment. In a similar way, other languages may impose different constraints on lexical organization given the structure of the language (e.g., syllabic structure in Italian, or moras in Japanese).

Although there has not yet been an attempt to model word recognition in Hebrew, an important question concerns the ability of current computational models of reading to generalize for other languages with alphabetic orthographies, and capture, for example, reading in a Semitic language. Albeit speculative, our analysis is based on the general principles on which these models are based. The question at hand is what type of model would be general enough to simultaneously account for reading of words with and without internal structure. In operational terms, what type of model can produce form-priming and TL priming for words like /agartal/ and no priming for derived words such as /tizkoret/?

The “triangular-model approach (e.g., Harm & Seidenberg, 1999, 2004; Plaut, McClelland, Seidenberg & Patterson, 1996), considers reading in terms of the mappings among orthography, phonology and semantics, and proposes that these are learned via associative mechanisms that are sensitive to the statistical properties of the representations and the mappings among them. At the heart of the triangle model is the notion that mappings among various properties of words are acquired by gradual learning of the statistics of the input. Hence, triangular models are set to “pick up” covariations and conditioned probabilities that determine phonological structure, modulated by high correlations between phonological forms and meaning. At least one simulation of this type of model produced greater sensitivity to morphological units in morphologically rich languages relative to morphologically impoverished ones (Plaut & Gonnerman, 2000). However, note that these models do not provide a clear account of TL priming effects in European languages. Hence, whether training the model on Hebrew derived words, and morphologically simple words would produce TL priming for the former and not for the latter remains to be seen.

Noisy letter-position models (e.g., as implemented in the noisy-position Bayesian Reader model, Norris, Kinoshita & van Casteren, 2010; The Overlap model, Gomez, Ratcliff & Perea, 2008) were designed from the onset to accommodate a set of orthographic effects such as transposed-letter priming, and they are indeed producing relatively good fits for languages in which base forms are represented as a linearly ordered sequence of letters and have no internal structure. However, in their current form, it would be beyond the scope of these models to capture the effects for structured base words.

Considering open-bigram encoding models (e.g., The SERIOL model, Whitney, 2001; Grainger & Whitney, 2004; Whitney, 2008), their clear advantage is that they rely on non-contiguous letter units, so that, in principle, they could pick-up the morphemic constituents of Hebrew base words, which are non-contiguous by definition. However, in order to produce different TL priming effects for Semitic and non-Semitic words, these models would have to assume an initial level of processing that extracts the roots from the open-bigram representation in Semitic words, where each root unit (or detector) would receive inputs from the three corresponding open-bigrams (e.g., the root z.k.r would receive inputs from ZK, ZR, and KR). Non-Semitic words, by contrast, are necessarily longer and hence their processing involves inputs from many more open-bigrams. By this view, any transposition of two letters within the root would result in activation of only 2/3 of the root detector, whereas for non-Semitic words, a larger proportion of the word detector units would be activated when two letters are transposed. Note that this account explains the effect of internal structure by focusing simply on the length of the detected unit: three root letters for Semitic words, and more letters for non-Semitic words. If the target of lexical search is a short unit of three letters, any letter transposition becomes critical. In general, TL priming increases with the length of the letter string, and on the average three-letter strings are less similar to each other than five- or six-letter strings. However, this account sets a lower-limit to TL priming effects predicting that in any language three-letter base words (or morphemes) would not produce priming.

This possible explanation regarding TL effects in Hebrew has the advantage of using the same principle for Hebrew and other languages, however, similar to Frost et al., 1997, 2005, it must assume that root extraction is the primary phase of visual word recognition in Semitic languages, and that lexical processing is primarily driven by morphemic root representations rather then the entire letter sequence. The evidence for a “Semitic” system that quickly extracts root morphemes and generates a morphologically-based code is indeed abundant. Root letter primes have been shown to facilitate root-derived targets more than any other letter sequence (e.g., Frost et al., 1997). Eye-movement studies have demonstrated that in contrast to English, Hebrew readers seek and extract root information already in the parafovea (Deutsch, Frost, Pollatsek & Rayner, 2000, 2005; Deutsch, Frost, Peleg, Pollatsek & Rayner, 2003). And finally, any changes in the typical Semitic structure of words have been shown to interfere with lexical access (Frost et al., 2000; Velan, Frost, Deutsch & Plaut, 2005). The present set of experiments supplements these findings to suggest that aside from these “Semitic” processing routines, Hebrew readers employ in parallel a lexical system that resembles that of other European languages. Hence, Hebrew words which are not root derivations are stored and processed like any base word in other alphabetic orthographies. Admittedly, this duality is not parsimonious; however, it probably ensures fast and efficient reading in a complex language that has words both with and without internal structure.

The qualitative difference in processing base forms with and without internal structure reflects, therefore, a deeper taxonomy, mainly the difference between orthographic and morphological processing. In languages such as English, French, or Spanish, base words are necessarily morphologically simple. Consequently, most current models of visual word recognition are constrained to orthographic processing of base words, and do not address the complexity of morphological decomposition. Indeed, it has been shown that well-established orthographic effects such as TL priming are abolished when stimuli are composed of morphologically complex words rather than base words, and transpositions occur across morphemic boundaries (e.g., Dunabeitia et al., 2007). The main difference between European and Semitic languages is that most Semitic base words have an internal structure since they are composed of two intertwined morphemes, that is, most base words are morphologically complex. Hence, for these languages an account of simple orthographic processing would not suffice. Modeling visual word recognition in these languages must involve morphological processing in parallel to orthographic processing. In other words, the problem with modeling Hebrew is not simply to “crack an orthographic code” (See Grainger, 2008), but rather to crack a *morpho-orthographic* code, that results in retrieving the three letters of the root. Admittedly, automatic morpho-orthographic segmentation has also been suggested in English (See Crepaldi, Rastle, Coltheart, & Nickels, 2010). However, in the case of English, prefixes and suffixes in English are always located at the beginning or end of base words so that their location is known in advance. More important, they are characterized by exceedingly high distributional properties. Hence their stripping involves a simple and shallow process (e.g., Longtin & Meunier, 2005; Rastle, Davis, & New, 2004; and see Rastle & Davis, 2008, for a review). In Hebrew, on the other hand, the constituent morphemes are intertwined. The position of the root letters in a given Hebrew word is not fixed, and depends on the specific word-pattern. Considering for example the word /tizkoret/, both z.k.r and k.r.t are legal meaningful roots. The system needs therefore to recognize that the final letter t in /tizkoret/ is a word-pattern letter and not a root letter. This feature, common to all Semitic languages, complicates the mechanism of morpho-orthographic segmentation significantly.

When considering “internal structure”, the results for words which have a Semitic word-pattern but contain a non-productive or pseudo-root, are especially intriguing. Whereas the findings for root-derived words such as /tizkoret/, and those for non-Semitic words such as /agartal/ seem clear-cut, the findings for words like /tarmil/ were inconclusive. In all experiments, the effects we obtained for these words fell somewhere “in-between” the two extremities. In Experiment 2, they more closely resembled the root-derived words, yet in Experiments 3 and 4, they better resembled the ”English-like” words, and at least in one experiment (Exp. 4), they displayed significant effects of form-priming, suggesting that Hebrew readers consider them to be non-Semitic. What makes these words interesting is that, on the one hand, they do have a recognizable word-pattern which unequivocally determines the root-morpheme slot, but on the other hand, lexical search based on a morphologically based code would result in a dead-end. One possibility to entertain is that words like /tarmil/ are dispersed in the two lexical systems differently for each reader, so that the results in this condition reflect the mean of two distributions for each individual participant. Another possibility is that these words are processed first as Semitic words, and at some point additional time becomes required in order to locate them, similar to derivations of weak-roots (Velan et al., 2005). These hypotheses, however, require additional investigation.

The present findings from Hebrew provide then an important challenge to current models of reading. Not only do they suggest that the basic principles of lexical organization in one alphabetic system may not apply to another alphabetic system, they suggest that even within one language, different principles of lexical organization are applied for words that have internal structure and words that do not. We would like then to argue that current models of visual word recognition are biased to some extent by the structure of Indo-European languages where most base words do not have any internal structure. Recently, Share (2008) has considered the impact of “Anglo-centricity” on theories of reading acquisition, focusing on the relevance of phonological awareness to reading. Using a similar line of argument, we suggest that models that consider only languages where base-words have minimal structure may miss important characteristics of the reading system, such as its tendency towards picking up statistical structure. This is the essence of an Ecological Theory of Reading (Frost, 2009): in order to model reading, reading acquisition, and reading disorders one needs to consider the full scope of the reader’s linguistic environment.

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Appendix

Appendix A

The Hebrew Alphabet

Hebrew Print	Orthographic Transcription	Phonetic Transcription
א		
ב	b	b / v
ג	g	g
ד	d	d
ה	h	h
ו	w	o / u / v
ז	z	z
ח	x	x
ט	θ	t
י	y	i / y
כ	k	k / x
[a]ך	K	x
ל	l	l
מ	m	m
[a]ם	M	m
נ	n	n
[a]ן	N	n
ס	S	s
ע	ς	
פ	p	p / f
[a]ף	P	f
צ	c	c
[a]ץ	C	c
ק	q	k
ר	r	r
ש	s	s / S
ת	t	t

[a] The letters q, m, n, p and c have different orthographic forms when they appear at the end of the word.

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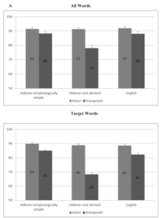

Figure 1.

Percent report of all the words of the sentence and of target words only, in English, in Hebrew morphologically simple and in Hebrew root-derived words, with normal (left bar) and with transposed (right bar) text. Upper bars represent SEM[iii].

[iii] Note that the graph does not start at zero.

Table 1

Examples of the stimuli used in Experiment 2

	Identity	**TL**	**Control**
Morphologically simple			
Orth. trans.	AGRTL	ARGTL	AKRTL
Hebrew	אגרטל	ארגטל	אקרטל
Phon. trans.	/agartal/		
Meaning	"a vase"		
Non-productive root			
Orth. trans.	TRMYL	TMRYL	TSMYL
Hebrew	תרמיל	תמריל	תשמיל
Phon. trans.	/tarmil/		
Meaning	"a backpack"		
Root-derived			
Orth. trans.	MKBSH	MKSBH	MKDSH
Hebrew	מכבסה	מכסבה	מכדסה
Root	k.b.S		
Phon. trans.	/maxbesa/		
Meaning	"a laundromat"		

Table 2

Mean Reaction times (msec), percent errors and priming effects for lexical decision for target words and nonwords in Experiment 2

	Identity	TL	Control
	Words		
Morphologically simple			
RT	502	520	540
Error	3.7%	5.0%	9.6%
Priming	+38**	+20**	
Non-productive root			
RT	504	547	555
Error	3.7%	12.3%	10.9%
Priming	+51**	+8	
Root-derived			
RT	505	540	537
Error	3.1%	9.0%	7.8%
Priming	+32**	−3	
	Nonwords		
RT	573	573	575
Error	5.2%	4.5%	4.5%
Priming	2	2	

[*] p < .05 for either participants ot items

[**] p < .05 for both participants and items

Table 3

Mean Reaction times (msec), percent errors and priming effects for lexical decision for target words and nonwords in Experiment 3

	Identity	**TL**	**Control**
	Words		
Morphologically simple			
RT	533	544	559
Error	1.1%	3.2%	4.2%
Priming	+26**	+15**	
Non-productive root			
RT	534	573	584
Error	1.8%	4.4%	5.4%
Priming	+50**	+11	
Root-derived			
RT	546	614	598
Error	1.9%	7.5%	7.8%
Priming	+52**	−16*	
	Nonwords		
RT	613	611	606
Error	3.5%	3.0%	2.7%
Priming	−7	−5	

[*] p < .05 for either participants to items

[**] p < .05 for both participants and items

Table 4

Examples of the stimuli used in Experiment 4

	Identity	Form	Control
Mask	#######	#######	#######
Morphologically simple			
Orth. trans.	AGRTL	AKRTL	HBXZM
Hebrew	אגךטל	אקרטל	הבחזם
Non-productive root			
Orth. trans.	TRMYL	TSMIL	DMWKH
Hebrew	תרמיל	תשמיל	דמוכה
Root-derived			
Orth. trans.	MXBSH	MXLSH	GLNWT
Hebrew	מכבסה	מכלסה	גלנות

Table 5

Mean Reaction times (msec), percent errors and priming effects for lexical decision to target words and nonwords in Experiment 4

	Identity	**Form**	**Control**
	Words		
Morphologically simple			
RT	501	537	550
Error	2.3 %	6.2%	8.2%
Priming	+49**	+13**	
Non-productive root			
RT	501	539	550
Error	2.3%	6.9%	5.8%
Priming	+49**	+11*	
Root-derived			
RT	499	534	540
Error	2.4%	7.5%	5.5%
Priming	+41**	+6	
	Nonwords		
RT	578	571	590
Error	4.7%	3.4%	4.7%
	12**	19**	

* p < .05 for either participants to items

** p < .05 for both participants and items