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The search for an input-coding scheme: Transposed-letter priming in Arabic

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Two key issues for models of visual word recognition are the specification of an input-coding scheme and whether these input-coding schemes vary across orthographies. Here, we report two masked-priming lexical decision experiments that examined whether the ordering of the root letters plays a key role in producing transposed-letter effects in Arabic—a language characterized by non-concatenative morphology. In Experiment 1, letter transpositions involved two letters from the root, whereas in Experiment 2, letter transpositions involved one letter from the root and one letter from the word pattern. Results showed a reliable transposed-letter priming effect when the ordering of the letters of the root was kept intact (Experiment 2), but not when two root letters were transposed (Experiment 1). These findings support the view that the order of the root letters is allowed only a minimum degree of perceptual noise to avoid the negative impact of activating the "wrong" root family.

Recent research has shown that a transposed-letter stimulus like *jugde* is very similar, perceptually, to *judge* (e.g., faster recognition of *jugde*–JUDGE than of *jupte*–JUDGE; Perea & Lupker, 2003a, 2003b; see also Perea & Carreiras, 2006; Schoonbaert & Grainger, 2004). The robustness of transposed-letter priming, which is an obvious problem for any model of visual word recognition using a slot-base coding scheme, has led to the appearance of more flexible input-coding schemes (e.g., SOLAR model, Davis, 1999; SERIOL model, Whitney, 2001; open-bigram model, Grainger & van Heuven, 2004; overlap model, Gomez, Ratcliff, & Perea, 2008). For example, in the overlap model (Gomez et al., 2008), the representation of a letter is normally distributed across ordinal positions in the letter string: In a five-letter pseudoword like *jugde*, the letter *d* is associated with Position 3, but also, to a lesser degree, with Positions 2 and 4 and even with Positions 1 and 5. This way, *jugde* and its base word, *judge*, are perceptually very close.

Here, we tackle the question of whether or not these input-coding schemes are universal to all orthographies (see Perea & Pérez, 2009, and Lee & Taft, 2009, for evidence of transposition effects in Japanese and Korean, respectively). To do that, we employed a transposed-letter manipulation in a non-concatenative morphology: Arabic. As in other Semitic languages (e.g., Hebrew), the root of a word in Arabic—which tends to be triconsonantal (e.g., the sequence *s.b.H* سبح [*to swim*])—has a key role in lexical access (see Frost, Kugler, Deutsch, & Forster, 2005, for evidence in Hebrew and Arabic; see also Boudelaa & Marslen-Wilson, 2005). Keep in mind that the meaning of an Arabic word is based exclusively on the consonants of the root, whereas the other letters—which form the *word pattern*—are used to create the desired inflection of meaning (see, e.g., Boudelaa & Marslen-Wilson, 2005, or Ibrahim, Eviatar, & Aharon-Peretz, 2002, for a review of orthographic and morphological processes in Arabic). In Semitic languages, each set of root letters, together with the word pattern, can lead to a vast number of words, mostly predictable in form and all related to the basic meaning of the root letters. For instance, the Arabic root *k.t.b* has the meaning of marking/writing; كاتب ("kAtib" = *writer*) and كتب ("katab" = *books*) are just a few instances of the use of this root.[1] Note that the letters of the root and the word pattern in Semitic languages may be intertwined: The root and the word pattern form two abstract discontinuous morphemes (see Boudelaa & Marslen-Wilson, 2005). Importantly, many roots share the same set of three letters, but in a different order; for example, the root *s.b.H* سبح ("to swim") can be altered to produce the roots *H.s.b* حسب

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("to calculate"), *H.b.s* حبس ("to imprison"), or *s.H.b* سحب ("to withdraw").

It has been proposed that lexical space in Semitic languages is not organized in orthographic terms, as in Indo-European language, the reason being that, in Semitic languages, lexical space would be organized according to root families (Frost, 2009). Consistent with this hypothesis, Velan and Frost (2009) showed that when the root letters of a nonword prime are transposed in Hebrew, the transposed-letter priming effect found in Indo-European languages is absent. In their Experiment 3, response times (RTs) to a target word such as *mdrgh*, whose root is *d.r.g*, were similar when the prime was the transposed-letter nonword prime *mrdgh*, which has the nonexisting root *r.d.g*, and when the prime was a replacement-letter nonword prime in which two letters from the root were replaced; furthermore, a condition that employed a transposed-letter root prime (*mgrdh*, a word that is derived from the existing root *g.r.d*) showed a small (11-msec) inhibitory effect, relative to the replacement-letter condition. Velan and Frost (2009) used the overlap model to explain their data: The order of the root letters would be allowed only a minimum degree of perceptual noise in an overlap-like model, to avoid the negative impact of activating the "wrong" root family. That is, letter ordering of a word's root letters would be critical in lexical access of Semitic languages (Velan & Frost, 2007).

One potential limitation of Velan and Frost's (2009) Experiment 3 is that they employed nonword primes. Although models of visual word recognition need to account for the reading of novel strings of letters, their main focus should be the identification of words (see Duñabeitia, Perea, & Carreiras, 2009). In the present experiments, we opted to employ word primes—always using existing roots—rather than nonword primes with nonexisting roots. Bear in mind that the processing of nonword stimuli—in particular, with a nonexisting root—may alter the normal processing within the lexical system in Semitic languages (see, e.g., Velan & Frost, 2007).

The rationale of the present study was the following. If the correct order of the root letters is vital to providing lexical access in Semitic languages, we would expect a facilitative transposed-letter priming effect with word primes when the letter transposition does not affect the ordering of the root letters, but not when primes and targets share all the letters, but two letters of the root are transposed. To test this hypothesis, we examined the impact of letter transposition in unpointed Arabic, using a masked-priming procedure. In Experiment 1, we employed word pairs in which two letters of the root were transposed (as in the word–word pair *E.b.y.d–b.E.y.d* عبيد–بعيد ["slaves–far"]; the roots are عبد [*E.b.d*] and بعد [*b.E.d*], respectively); note that transposed-letter primes and targets were not morphologically related—that is, their roots were different. In Experiment 2, we used word pairs in which the transposition was between one letter from the root and a letter from the word pattern (as in the word–word pair *q.y.A.s–y.q.A.s* قياس–يقاس ["measurement–will be measured"]; the root is قاس [*q.y.s*] in both cases); note that transposed-letter primes and targets were morphologically related (i.e., the roots were the same).

Interestingly, Duñabeitia et al. (2009) obtained the usual transposed-letter priming effect with nonword–word pairs in Spanish (e.g., *comsos*–COSMOS) but failed to show any transposed-letter priming effects when using word–word pairs that did not have any semantic/morphological relationship (e.g., *cerdo*–CEDRO; the Spanish for *pig*–CIDER). The lack of transposed-letter priming for word primes in the Duñabeitia et al. (2009) study occurred both when the control condition was a replacement-letter prime word and when the control condition was an unrelated prime word. In the present experiments, we chose unrelated word primes as the control condition, since this allowed us to select a higher number of stimuli per condition than would have replacement-letter word primes; in any case, keep in mind that form-priming effects in Semitic languages (in the absence of a morphological relation) using one-letter-different primes tend to be negligible (Frost et al., 2005).

Finally, we also examined whether transposed-letter priming differs as a function of the position of the letter transposition in Arabic. We employed word pairs in which the transposition occurred in an initial position, in a middle position, and in the final position. In Indo-European languages, transposed-letter priming effects tend to be greater for internal transpositions than for external transpositions (Perea & Lupker, 2003a, 2003b, 2007). However, if the correct ordering in the root letters is the key factor in lexical access in Semitic languages, as was proposed by Frost (2009), the influence of position in modulating the magnitude of the transposed-letter priming effect should be much smaller than in Indo-European languages.

As in most transposed-letter priming experiments, we used a lexical decision task. To avoid physical continuity between primes and targets (note that Semitic languages do not have the lowercase/uppercase distinction), primes were presented in 14-point font, and targets were presented in 18-point font.

EXPERIMENT 1

Method

Participants. Twenty-six students from the University of Amman took part in this experiment voluntarily. All of them were native speakers of Arabic, used Modern Standard Arabic on a daily basis, and had normal or corrected-to-normal vision.

Materials. We selected a set of 120 Arabic words; 112 were multimorphemic, and 8 were monomorphemic. The mean frequency of these words was 7.4 appearances per million (range, 1–64.4) in the Modern Standard Arabic database (Aralex database; Boudelaa & Marslen-Wilson, 2010), and their mean length was 4.1 (range: 4–6). All these words had a higher frequency transposed-letter neighbor, and the mean number of substitution neighbors was 11.8 (range, 2–28). These words were preceded by prime words that were (1) a transposed-letter word neighbor with a transposition of two letters from the root (*E.b.y.d–b.E.y.d* عبيد–بعيد ["slaves–far"]; the roots are عبد [*E.b.d*] and بعد [*b.E.d*]) or (2) an unrelated word (*>lyp–Beyd* ألية–بعيد). The letter transposition occurred in the initial, middle, or final position (40 word pairs in each case; mean frequency of the word targets, 7.5, 8.1, and 6.5, respectively; mean log bigram frequency

Table 1
Transposed-Letter Word Primes and the Corresponding Target Words in Experiments 1 and 2

Transposed-Letter Prime	Unrelated Prime	Target	Position
	Experiment 1: Different Root		
Ebyd (عبيد) (slaves)	>lyp (آلية) (mechanism)	Beyd (بعيد) (far)	Initial
MqEd (مقعد) (seat)	xdAm (خادم) (servant)	Meqd (معقد) (complex)	Middle
Tklf (تكلف) (will cost)	EddA (عددا) (number)	Tkfl (تكفل) (ensure)	Final
	Experiment 2: Same Root		
qyAs (قياس) (measurement)	ydwr (يدور) (turning)	yqAs (يقاس) (will be measured)	Initial
frAg (فراغ) (vacuum)	bnwd (بنود) (items)	fArg (فارغ) (empty)	Middle
jmyE (جميع) (all)	mwqf (موقف) (position)	jmEy (جمعي) (collective)	Final

in the Aralex database, 3.3, 3.3, and 3.3, respectively; see Table 1 for examples). The transposed-letter and unrelated primes always had a higher word frequency than did the corresponding target words (mean frequency, 43 vs. 41, respectively). The list of the prime–target stimuli is available at the following Web site: www.uv.es/mperea/TL_PMC.pdf. An additional set of 120 legal nonwords in Arabic was created for the purposes of the lexical decision task. The target nonwords were matched to the target words in length (mean, 4.1; range, 4–5). The manipulation of the pseudoword trials was the same as that for the word trials (i.e., a transposed-letter prime vs. an unrelated prime). Two lists of materials were constructed so that each target appeared once in each list, but each time in a different priming condition (transposed-letter neighbor or unrelated). Different groups of participants were given the two lists.

Procedure. The participants were tested individually or in groups of 2 in a quiet room. Presentation of the stimuli and recording of RTs were controlled by PC-compatible computers. The experiment was run using DMDX (Forster & Forster, 2003). RTs were measured from target onset to the participant's response. On each trial, a forward mask consisting of a row of hash marks (#s) was presented for 500 msec in the center of the screen. Next, the prime was presented in 14-point Arabic font and stayed on the screen for 50 msec (three cycles, each cycle corresponding to 16.6 msec on the CRT monitor). The prime was followed immediately by the presentation of the target stimulus in 18-point Arabic font. Both the prime and target were presented in the same screen location as the forward mask. The target remained on the screen until the participants responded. The participants were instructed to press one of two buttons on the keyboard to indicate whether the letter string was a legitimate word in Arabic or not. The participants were instructed to make this decision as quickly and as accurately as possible. They were not informed of the presence of briefly presented stimuli, and none of them reported (after the experiment) conscious knowledge of the existence of any prime. Each participant received a different order of trials. Each participant received a total of 20 practice trials (with the same manipulation as in the experimental trials) prior to the 240 experimental trials. The whole session lasted approximately 15 min.

Results and Discussion

Incorrect responses (12.5% of the data for word targets) and RTs beyond the 250- to 1,500-msec cutoff values (less than 1.2%) were excluded from the latency data. The mean latencies for correct responses and error rates are presented in Table 2. ANOVAs based on the participant and item response latencies and error percentages were conducted on the basis of a 3 (position of transposition: initial, internal, final) × 2 (prime–target relatedness: transposed letter, unrelated) × 2 (list: List 1, List 2) design. List was included as a dummy variable to extract the variance due to the counterbalancing lists (Pollatsek & Well, 1995).

Word targets. The ANOVA on the latency data showed only a significant effect of position [$F_1(2,48) = 10.23$, $p < .001$; $F_2(2,114) = 6.10$, $p < .004$]; post hoc Tukey tests showed that RTs were longer for the middle position than for the final position. Neither the main effect of transposed-letter priming nor the interaction between the two factors approached significance (all Fs < 1).

The ANOVA on the error data showed only a significant effect of position in the analysis by participants [$F_1(2,48) = 6.433$, $p < .004$; $F_2(2,114) = 1.24$, $p > .20$]; a post hoc Tukey analysis showed that error rates were higher in the initial position than in the other two positions in the analysis by participants. The other effects were not significant.[2]

Nonword targets. None of the effects in the ANOVA on the latency/error data were significant, although there was a nonsignificant trend toward a transposed-letter priming effect in the error data [$F_1(1,24) = 3.56$, $p = .071$; $F_2(1,114) = 2.99$, $p = .087$].

The results are clear-cut. There were no signs of a transposed-letter priming effect—a nonsignificant −4 msec effect—with word primes when the transposition occurred between two letters from the root, as in *E.b.y.d–b.E.y.d* عبيد–بعيد (the roots are عبد [*E.b.d*] and بعد [*b.E.d*]). This is consistent with the view that the correct order of the root letters plays a key role in visual word recognition in Semitic languages.

In Experiment 2, we used transposed-letter word pairs in which the order of the letters of the root were not transposed (i.e., the transposition occurred between a root letter and a letter from the word pattern). In Experiment 2, related primes and targets shared the same root, and one would expect a facilitative transposed-letter priming effect; they are morphologically related.

EXPERIMENT 2

Method

Participants. Twenty-eight students from the University of Amman took part in this experiment voluntarily. All of them were native speakers of Arabic and had normal or corrected-to-normal vision.

Materials. We selected a set of 120 Arabic words; 107 were multimorphemic, and 13 were monomorphemic. The mean frequency of these words was 14 appearances per million (range, 1–166) in the Aralex database (Boudelaa & Marslen-Wilson, 2010), and their mean length was 4.2 (range, 4–6). The mean number of sub-

Table 2
Mean Lexical Decision Times (LDTs, in Milliseconds) and Percentages of Errors (PEs) for Word and Pseudoword Targets in Experiment 1 (Different Root)

	Transposed		Unrelated		Priming	
	LDT	PE	LDT	PE	LDT	PE
Word Trials						
Initial position	598	13.8	597	15.2	−1	1.4
Middle position	611	12.1	607	12.1	−4	0.0
Final position	580	11.3	574	10.6	−6	−0.6
Nonword Trials						
Initial position	637	11.7	634	15.0	−3	3.3
Middle position	622	9.2	627	12.3	5	3.1
Final position	618	10.4	628	9.8	10	−0.6

stitution neighbors was 7.9 (range, 1–25). These words were preceded by prime words in Arabic that were (1) a transposed-letter word neighbor formed by transposing a root letter and a letter of the word pattern (*q.y.A.s–y.q.A.s* يقاس–قياس ["measurement–will be measured"]; the root is قاس [*q.y.s*] in both cases) or (2) an unrelated word (*j.r.A.'–y.q.A.s* يقاس–جراء). As in Experiment 1, the letter transposition occurred in the initial, middle, or final position (40 word pairs in each case; mean frequency of the word targets, 11.3, 17.4, and 12.7, respectively; mean log bigram frequency, 3.4, 3.4, and 3.3, respectively; see Table 1 for examples). The transposed-letter and unrelated primes always had a higher word frequency than did the corresponding target words (mean frequency, 154 vs. 126, respectively). The list of the prime–target stimuli is available at the following Web site: www.uv.es/mperea/TL_PMC.pdf. An additional set of 120 legal nonwords in Arabic was created for the purposes of the lexical decision task. The target nonwords were matched to the target words in length (mean, 4.1; range, 4–6). The manipulation for the pseudoword trials was the same as that for the word trials (i.e., a transposed-letter prime vs. an unrelated prime). Two lists of materials were constructed so that each target appeared once in each list, but each time in a different priming condition (transposed-letter neighbor or unrelated). Different groups of participants were given the two lists.

Procedure. The procedure was the same as that in Experiment 1.

Results and Discussion

Incorrect responses (11.2% of the data) and RTs beyond the 250- to 1,500-msec cutoff values (less than 1.6%) were excluded from the latency data. The mean latencies for correct responses and error rates are presented in Table 3. ANOVAs based on the participant and item response latencies and error percentages were conducted on the basis of a 3 (position of transposition: initial, internal, final) × 2 (prime–target relatedness: transposed letter, priming) × 2 (list: List 1, List 2) design.

Word targets. The ANOVA on the latency data showed a significant effect of position [$F_1(2,52) = 24.29$, $p < .001$; $F_2(2,114) = 8.12$, $p < .002$]; post hoc Tukey tests showed that RTs were longer for the final position than for the initial position. More important, target words preceded by a transposed-letter prime were responded to more quickly than were those words preceded by an unrelated word prime [$F_1(1,26) = 4.44$, $p < .05$; $F_2(1,114) = 19.84$, $p < .001$]. The interaction between the two factors did not approach significance (both Fs < 1).

The ANOVA on the error data showed a significant effect of position [$F_1(2,52) = 12.11$, $p < .001$; $F_2(2,114) = 6.66$, $p < .003$]; a post hoc Tukey analysis showed that error rates were higher in the initial position than in the final position. In addition, target words preceded by a transposed-letter prime were responded to with fewer errors than were those words preceded by an unrelated word prime, but the effect did not reach significance [$F_1(1,26) = 2.93$, $p = .09$; $F_2(1,114) = 3.01$, $p = .086$]. The interaction between the two factors did not approach significance (all Fs < 1).

Nonword targets. The ANOVA on the latency data showed only a significant effect of position [$F_1(2,52) = 5.68$, $p < .008$; $F_2(2,114) = 4.74$, $p < .02$]; a post hoc Tukey analysis showed that error rates were higher in the initial position than in the medial position. The other effects did not approach significance.

The results are straightforward. When the letter transposition occurred between a letter of the root and a nonroot letter (i.e., keeping the ordering of the root intact), there was a robust (16-msec) transposed-letter priming effect for word pairs (see note 2). Furthermore, this effect was numerically similar for initial, middle, and final transpositions.

GENERAL DISCUSSION

The main findings of these transposed-letter priming experiments with word pairs in Arabic are straightforward: There is a reliable priming effect when the ordering of the root letters is kept intact (Experiment 2), but not when two root letters are transposed (Experiment 1). This is consistent with the view that the order of the root letters is allowed only a minimum degree of perceptual noise to avoid the negative impact of activating the "wrong" root family.

The present data add further evidence to the view that lexical space in Semitic languages is defined by root families, so that "all words derived from a given root are clustered together" (Velan & Frost, 2007, p. 916; see also Frost et al., 2005; Velan & Frost, 2009). Given that transposed-letter priming with word primes does not occur in the absence of a morphological/semantic relationship—as was shown in Experiment 1 when primes and targets were derived from different roots (see also Duñabeitia et al., 2009, for evidence in Spanish)—the

Table 3
Mean Lexical Decision Times (LDTs, in Milliseconds) and Percentages of Errors (PEs) for Word and Pseudoword Targets in Experiment 2 (Same Root)

	Transposed		Unrelated		Priming	
	LDT	PE	LDT	PE	LDT	PE
Word Trials						
Initial position	575	6.6	598	7.3	23	0.7
Middle position	607	9.5	617	12.3	10	2.8
Final position	635	15.4	650	16.6	15	1.2
Nonword Trials						
Initial position	685	12.1	698	14.1	13	2.0
Middle position	661	10.5	655	11.6	−9	1.1
Final position	670	13.2	681	12.3	11	−0.9

transposed-letter priming effect observed in Experiment 2 is best interpreted as a root-priming effect (i.e., a morphological effect).[3]

One other important finding is that the magnitude of the transposed-letter effect for word pairs in Arabic is similar across letter positions (Experiment 2). (In Indo-European languages, transpositions involving initial or final letters are detrimental; see e.g., Perea & Lupker, 2003a, 2003b, 2007.) This is again consistent with the idea that lexical organization in Indo-European languages takes into consideration the full orthographic structure, whereas in Arabic (and presumably, other Semitic languages), lexical access is determined mainly by locating a root entry.

What are the implications of this finding for the input-coding scheme of models of visual word recognition? In an overlap model, letter location of the root letters would need to be precise, so that there would be a rather rigid relative position coding to activate the letters that compose a given root (see Velan & Frost, 2009). In contrast, the input-coding schemes that use open bigrams (e.g., Grainger & van Heuven, 2003; Whitney, 2001) or a spatial coding (Davis, 1999) run into difficulties when dealing with Hebrew data, because the internal structure of Semitic languages dictates the sequence of letters and this is quite different from the less constrained orthographic structure of Indo-European languages (see Velan & Frost, 2009).

One important question is whether the present findings can be used to justify the hypothesis that Semitic languages differ qualitatively from (pre)Indo-European languages. There are indeed some obvious differences regarding transposition effects. Unlike in Semitic languages, the transposition of two letters from the lexeme in (pre)Indo-European languages does not eliminate the transposed-letter priming effect (Duñabeitia, Perea, & Carreiras, 2007). Furthermore, unlike in Semitic languages, letter transposition effects in (pre)Indo-European languages are modulated by morpheme boundaries (Christianson, Johnson, & Rayner, 2005; Duñabeitia et al., 2007). Thus, although morphology interacts with letter position coding in the two families of languages, lexical access in Arabic is determined by locating a root entry, whereas lexical access in (pre)Indo-European languages depends to a greater degree on the full orthographic structure.

In sum, the present experiments demonstrate that word processing in a Semitic language (Arabic) is comparatively different from that in Indo-European languages. A robust transposed-letter priming effect with word primes emerged only when the transposition did not affect the order of the root letters. This implies a lexical system in which the detection of the identity/position of the root letters is vital for an efficient processing of the printed stimuli. Further research is needed to examine the similarities/differences between Indo-European and Semitic languages.

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NOTES

1. For the transcriptions, we used the Buckwalter transliteration scheme (see Boudelaa & Marslen-Wilson, 2010).

2. In Arabic, letters may show different patterns of connectivity—as in يدور versus عبيد. Thus, it may be relevant to examine whether the transposed-letter priming effect is modulated by the connectivity of the word prime. Results showed a similar transposed-letter priming effect for word pairs with the same pattern of connected letters (16 msec; e.g., تكفل–تكلف) and for word pairs with a different pattern of connected letters (20 msec; e.g., يحصر–يحرص). Note that this is consistent with the view that letters are processed at a quite abstract level early in processing—as is commonly assumed by most researchers.

3. In Experiment 2, out of the 120 word pairs, 77 were noun–noun pairs and 43 were noun–verb pairs. As a reviewer pointed out, noun–noun pairs may not be linguistically as similar as noun–verb pairs, and, thereby, they might show a reduced priming effect. However, the priming effects were similar for the two groups of relationships: 17 and 22 msec for noun–noun and noun–verb pairs. Note that the observed pattern is consistent with the idea that transposition effects have a very early locus (see Gomez et al., 2008).

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