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Extending Models of Visual-Word Recognition to Semicursive Scripts: Evidence From Masked Priming in Uyghur

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One basic feature of the Arabic script is its semicursive style: some letters are connected to the next, but others are not, as in the Uyghur word يا خشى /ya xʃi/ (“good”). None of the current orthographic coding schemes in models of visual-word recognition, which were created for the Roman script, assign a differential role to the coding of within letter “chunks” and between letter “chunks” in words in the Arabic script. To examine how letter identity/position is coded at the earliest stages of word processing in the Arabic script, we conducted 2 masked priming lexical decision experiments in Uyghur, an agglutinative Turkic language. The target word was preceded by an identical prime, by a transposed-letter nonword prime (that either kept the ligation pattern or did not), or by a 2-letter replacement nonword prime. Transposed-letter primes were as effective as identity primes when the letter transposition in the prime kept the same ligation pattern as the target word (e.g., ئنتايين - ئتنايين /inta_jin/-/itna_jin/), but not when the transposed-letter prime didn’t keep the ligation pattern (e.g., سوغۋات - سوۋغات /so_w_ʁa_t/-/so_ʁw_a_t/). Furthermore, replacement-letter primes were more effective when they kept the ligation pattern of the target word than when they did not (e.g., سوۋغات - سودچات /so_d_ʧa_t/-/so_w_ʁa_t/ faster than سوۋغات - سوچدات /so_ʧd_a_t/-/so_w_ʁa_t/). We examined how input coding schemes could be extended to deal with the intricacies of semicursive scripts.

Keywords: masked priming, letter position coding, lexical access, lexical decision

When letters within a word are scrambled, the resulting string can be easily misperceived as its base word, as is the case of *JUGDE* (*JUDGE*) (O’Connor & Forster, 1981). Likewise, masked priming experiments have revealed that the brief presentation of a transposed-letter prime like *jugde* activates the target word *JUDGE* nearly to the same degree as the identity prime *judge*, and substantially more than the replacement-letter prime *jupte* (Forster, Davis, Schoknecht, & Carter, 1987; Perea & Lupker, 2003, 2004; see also Johnson, Perea, & Rayner, 2007, for similar evidence with the boundary technique during normal silent reading).

The robustness of letter transposition effects across a variety of tasks and languages has led scholars to propose highly flexible orthographic coding schemes (e.g., spatial coding model, Davis, 2010; SERIOL model, Whitney, 2001; overlap model, Gomez, Ratcliff, & Perea, 2008; open-bigram model, Grainger & van Heuven, 2003; LTRS model, Adelman, 2011; noisy-slot Bayesian reader model, Norris, Kinoshita, & van Casteren, 2010). All these models have been quite successful in dealing with the intricacies of letter position coding during visual-word recognition in the Roman script—that is, the most widely used script in the world. One remaining issue is whether these orthographic coding schemes can be readily generalized to other alphabetic scripts or whether it is critical to consider the peculiarities of each script. Here we focus on another widely used script: Arabic. This script is used not only for the Arabic language, but also for Persian, Kurdish, Urdu, Pashto, Sindhi, and Uyghur, among other languages. The present research was conducted in Uyghur. Uyghur belongs to the family of Turkic languages and is the official language in the Xinjiang-Uyghur Autonomous Region in China.

There are two main reasons why we chose Uyghur rather than Arabic. First, Uyghur represents *all* letters in print, both consonants and vowels, thus providing a better comparison to the languages that employ the Roman script; in contrast, Arabic only represents partial vowel information. For example, the Uyghur word for paper is ۋاراق (transliterated as /waraq/), while the Arabic word for paper does not have any printed vowel information ورق (transliterated as /wrq/). Second, similar to other Turkic languages, Uyghur is an agglutinative language that does not have a

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rigid “root and word-pattern” structure that constrains letter position coding in Semitic languages (see Velan & Frost, 2007; Perea, Abu Mallouh, & Carreiras, 2010, for evidence in Hebrew and Arabic, respectively; see also Lerner, Armstrong, & Frost, 2014, for simulations). Thus, when examining letter position coding, Uyghur presents a scenario comparable to that provided by other agglutinative languages (e.g., Basque) that use the Roman script (see Duñabeitia, Perea, & Carreiras, 2007; Perea & Carreiras, 2006, for evidence of transposed-letter effects in Basque), but, critically, Uyghur uses the Arabic script.

The Arabic script has a number of salient characteristics in Uyghur. Leaving aside that there is no lowercase/uppercase distinction and that it is read from right to left, this script has two relevant features. First, it is semicursive: some of the words’ constituent letters are connected to the previous letter (e.g., the letters پ and ت are combined as پت), whereas others are not (e.g., the letters د and ر would result in در). In particular, the letters that cannot be connected to the following letter are: ا د ر ز ە و ۇ ۆ ۈ ژ ۋ. As a result, words in Arabic script are constituted by one or several “graphemic chunks” (also called Parts-of-Arabic-Word [PAWs] or subwords), as in the case of مېھمىنىمنىڭ /méhminimniŋ/, “my guest’s” (one PAW), يا خشى /ya_xʃi/, “good” (two PAWs), or تۇ ر مۇ ش, /tu_r_mu_ʃ/, “life” (four PAWs). (To highlight the distinction between PAWs, we have added underlined spaces in the transliterated words.) Indeed, it has been proposed that there may be a layer of PAWs between the letter level and whole-word level (see Belaïd & Choisy, 2006), such that the Uyghur word /inta_jin/ ئىنتايىن would activate *i-n-t-a-j-i-n* at the letter level, *inta-jin* at the “graphemic chunk” (PAW) level, and *itnajin* at the word level. Indeed, there may a processing unit not only for words but also for PAWs. That is, for a reader with no knowledge of Arabic, it may not be easy to separate in a sentence which letter strings form a word and instead which are part of a PAW within a word, as can be seen in the following example:

بۇ بارىمادا چوك ئاپام بىزگە سوغۇات بەردى. “In this festival, our grandmother gave us a gift” the correct separation between words is the following:

بۇ بارىمادا چوك ئاپام بىزگە سوغۇات بەردى.

Second, the visual form of each letter may differ depending on its position within the graphemic chunk (initial, middle, final, or isolated). For example, the letter /p/ is in the initial form (پـ) in the Uyghur word /pɛ_r_w_a_z/ پەرۋاز, it is in the middle form (ـپـ) in the word /iptixa_r/ ئىپتىخار “proudness,” it is in the final form (ـپ) in the word /sinip/ سىنىپ “classroom,” and it is in the isolated form (پ) in the word /sa_p/ ساپ “handle” (see Engesæth, Yakup, & Dwyer, 2009, for an introduction to Uyghur language). Indeed, while children learn the Roman alphabet with letters in lowercase/uppercase, children learn the Arabic alphabet with letters in initial/middle/final/isolated forms (see Table 1, for a depiction of the different allographic forms in Uyghur).

The main goal of the present experiments is to examine how letter identity/position is coded at the earliest stages of word processing in the Arabic script. Two recent studies in the Arabic script have demonstrated that its semicursive style plays a role during visual-word recognition. Friedmann and Haddad-Hanna (2012) conducted a naming study in Arabic with three individuals that suffered from letter position dyslexia. Participants had to pronounce words that had a transposed-letter neighbor—the parallel example in English would be to pronounce *CAUSAL* (the transposed-letter neighbor is *CASUAL*; see Acha & Perea, 2008).

Table 1
Illustration of Letter-Position Allographs in Uyghur

IPA	Isolated form	Final form	Middle form	Initial form
a	ا	ـا	ـئا	ئا
ɛ/ æ	ە	ـە	ـئە	ئە
b	ب	ـب	ـبـ	بـ
p	پ	ـپ	ـپـ	پـ
t	ت	ـت	ـتـ	تـ
ʤ	ج	ـج	ـجـ	جـ
ʧ	چ	ـچ	ـچـ	چـ
x	خ	ـخ	ـخـ	خـ
d		ـد		د
r		ـر		ر
j		ـز		ز
ʒ		ـژ		ژ
s	س	ـس	ـسـ	سـ
ʃ	ش	ـش	ـشـ	شـ
ʁ	غ	ـغ	ـغـ	غـ
f	ف	ـف	ـفـ	فـ
q	چ	ـق	ـقـ	قـ
k	ك	ـك	ـكـ	كـ
ŋ	ڭ	ـڭ	ـڭـ	ڭـ
g	گ	ـگ	ـگـ	گـ
l	ل	ـل	ـلـ	لـ
m	م	ـم	ـمـ	مـ
n	ن	ـن	ـنـ	نـ
h			ـھـ	ھـ
o	و	ـو		ئو
u	ۇ	ـۇ		ئۇ
ø	ۆ	ـۆ		ئۆ
y	ۈ	ـۈ		ئۈ
w		ـۋ		ۋ
e	ې	ـې	ـېـ	ئېـ، ې
i/ɪ	ى	ـى	ـىـ	ئىـ، ى
j	ي	ـي	ـيـ	يـ

Participants made a substantial number of errors (with error rates of 85%) when the transposed-letter neighbor of the target word was composed of letters with the same ligation pattern (e.g., تمهل [slowed, tmhl] was frequently misread as تهمل [neglect, thml]; note that “m” and “h” are in their middle forms in the two words and are part of the same PAW), but made few errors (with error rates around 1%–16%) when the transposed-letter neighbor was composed of letters from different PAWs (e.g., the word شراع [*sail*, *$r_A_E*] was not misread as شارع [*street*, *$_A_rE*]).

To examine whether this finding could be generalized to adult skilled readers, Yakup, Abliz, Sereno, and Perea (2014) conducted a Rapid Serial Visual Presentation (RSVP) experiment in Uyghur. Half of the sentences were presented intact and the other half included jumbled words (i.e., nonwords created by the transposition of two letters). The participants’ task was to report the sentences by reproducing the words in the correct form, regardless of whether they were presented intact or jumbled. Participants were able to reproduce the jumbled words more accurately when the letters that composed the jumbled word had the same ligation pattern as the original Uyghur word (e.g., /itna_jin/ ئىتنايىن and

/inta_jin/ ئىنتايىن ; note that "t" and "n" are in their middle form from the same PAW in the two cases) than when the jumbled word had letters in different PAWs (e.g., */so_w_ʁa_t/* سوۋغات ["w" in isolated form and "ʁ" in final form] and */so_wʁ_a_t/* سوغۋات ["w" in final form and "ʁ" in initial form]). Yakup et al. (2014) conducted analyses that ruled out that this dissociation was due to visual similarity at a semiretinotopic level of processing. Echoing the claims originally put forward by Friedmann and Haddad-Hanna (2012), Yakup et al. (2014) concluded that for "scripts with letter position allography, although a word's graphemic representation may be invariant to irrelevant parameters, such as position, size, or font, the specific allograph (i.e., whether the letters appear in the initial, middle, or final part of the graphemic chunks) forms an integral part of the word's graphemic representation" (pp. 1604–1605).

Unfortunately, neither the naming task used by Friedmann and Haddad-Hanna (2012) with impaired individuals nor the RSVP task used by Yakup et al. (2014) can inform the temporal locus of the obtained effects. The goal of the present experiments was to examine the impact of the ligation pattern on letter identity/position during the early stages of visual-word recognition in an Arabic-Persian script (Uyghur). To that end, we employed a masked priming technique (Forster & Davis, 1984) together with a common laboratory word identification task, lexical decision. In this technique, a briefly presented prime (preceded by a pattern mask) is followed by a target stimulus. Under these conditions, participants are rarely aware of the identity, or even the existence, of the prime stimulus. It is important to note here that masked priming effects in lexical decision are based on the fast activation of abstract lexical codes rather than on visual familiarity. Cross-case visually dissimilar pairs (edge-EDGE < area-EDGE) produce a masked repetition priming effect of similar magnitude as cross-case visually similar pairs (kiss-KISS < soon-KISS) (Bowers, Vigliocco, & Haan, 1998; Perea, Jiménez, & Gómez, 2014). Furthermore, masked primes that are nominally but not physically the same as the target (e.g., crash-CRASH) are as effective as the masked primes that are physically and nominally the same as the target (CRASH-CRASH) (see Jacobs, Grainger, & Ferrand, 1995; Perea et al., 2014). Likewise, visually unfamiliar, alternating case masked primes (e.g., cRaSh-CRASH) are as effective as lowercase primes (crash-CRASH) (Forster, 1998; Perea, Vergara-Martínez, & Gomez, 2015). As Perea, Vergara-Martínez, and Gomez (2015) concluded, "masked priming effects in lexical decision occur at a level of abstract representations, regardless of visual familiarity" (p. 42).

Using a masked priming methodology, the present experiments examined how letter identity and position is coded in Uyghur. Experiment 1 examined the presence of letter transposition effects in Uyghur when the letter transposition did not alter the ligation pattern (same-ligation TL prime) (e.g., /inta_jin/, ئىنتايىن , "very" vs. /itna_jin/ ئىتنايىن; "t" and "n" are part of the same PAW in the same form positions [middle]) and when the letter transposition altered the ligation pattern (different-ligation TL prime) (e.g., /so_w_ʁa_t/ سوۋغات, "gift" vs. /so_ʁw_a_t/, سوغۋات ; where "w" and "ʁ" are in different PAWs, or they form part of the same PAW, respectively; note that in this scenario, letter-position markers are necessarily different: "w" is in isolated form position in the first stimulus, where it is in final form position in the second stimulus, "ʁ" is in initial letter form in the first stimulus, whereas it is in initial letter form in the second stimulus). The letter transposition always involved two consonant letters from the lexeme (see Duñabeitia et al., 2007, for evidence of transposed-letter priming with a similar manipulation in another agglutinative language [Basque] in the Roman script). We employed a different set of words for the same- versus different-ligation manipulation because of the severe constraints in selecting the appropriate target words in a within-item manipulation (see Yakup, Abliz, Sereno, & Perea, 2014, for discussion).

To examine the degree to which the transposed-letter prime (TL prime) activated the target words, we employed two control primes: (a) an identity prime (ID prime); and (b) a two-letter replacement prime (RL prime; e.g., see Perea & Lupker, 2003, 2004). An example of the prime-target pairs used in Experiment 1 is shown in Table 2. The identity prime is an optimal control because it contains exactly the same letters as the transposed-letter prime, the only difference being that they are in the correct position in the identity prime. The RL prime substitutes the transposed letters with different letters. These new letters retain the same position-dependent forms as the letters in the transposed-letter condition, except that the two letters are different. Note that the RL prime (i.e., an additional control for the transposed-letter prime) cannot separate the effects of letter position versus letter identity.

Thus, each same- and different-ligation target word in Experiment 1 was preceded by one of three primes: an identity (ID) prime, a transposed-letter (TL) prime, and a two-letter replacement (RL) prime. In Experiment 2, we directly examine whether the ligation pattern plays a role using two-letter replacement nonword primes. Specifically, we compared pairs that kept the ligation pattern or not (e.g., ئىجسايىن - ئىنتايىن [/idʒsa_jin/-/inta_jin/] vs. ئىرسايىن - ئىنتايىن /ir_sa_jin/-/inta_jin/]; سودچات - سوۋغات [/so_d_ʧa_t/-/so_w_ʁa_t/] vs. سوچدات - سوۋغات [/so_ʧd_a_t/-/so_w_ʁa_t/]). (We defer a more detailed explanation of the rationale of Experiment 2 until the Discussion section of Experiment 1.) As usual in languages that do not have a lowercase/uppercase distinction (e.g., Hebrew, Velan & Frost, 2011; Arabic, Perea, Abu Mallouh, & Carreiras, 2010; Thai, Perea, Winskel, & Ratitamkul, 2011; Japanese Kana, Perea & Pérez, 2009), primes were presented in a smaller font than the target.

The predictions from Experiment 1 are clear-cut. If letters are rapidly translated into an abstract orthographic code in which PAW information is lost, we should observe exactly the same pattern of priming effects regardless of whether the transposed or replaced letters have the same or different ligation pattern (i.e.,

Table 2
Examples of the Stimuli Used in Experiment 1

	Identity	Transposed-letter	Replacement-letter
Same-ligation pattern	ئىنتايىن	ئىتنايىن	ئىجسايىن
Phonological transcription	/inta_jin/	/itna_jin/	/idʒsa_jin/
Different-ligation pattern	سوۋغات	سوغۋات	سوچدات
Phonological transcription	/so_w_ʁa_t/	/so_wʁ_a_t/	so_ʧd_a_t/

ID ≤ TL < RL; e.g., see Perea & Lupker, 2003). Alternatively, if PAW information from the prime stimulus is retained and affects the early processing of the target word, then the orthographic similarity of the identity condition and the transposed-letter condition should be greater when prime and target share the same ligation pattern (/inta_jin/, ئنتايين, "very" vs. /itna_jin/ئتنايين) than when prime and target do not share the ligation pattern (/so_w_ʁa_t/ سوۋغات, "gift" vs. /so_ʁw_a_t/, سوغۋات).

Experiment 1

Method

Participants. Fifty-seven undergraduate students from Xinjiang University with normal/corrected-to-normal vision participated voluntarily in the experiment. All of them were native speakers of Uyghur.

Materials. We selected a total of 102 Uyghur words to serve as targets. The "same-ligation" set and the "different-ligation" set were each composed of 51 target words. Each target word was preceded by a prime that is: (a) the same as the target word (identity condition); (b) the same as the target except for the transposition of two internal adjacent letters (consonants; transposed-letter condition); and (c) the same as the transposed-letter primes except that the transposed letters were replaced by different letters (consonants; replacement-letter condition). For example, the same-ligation target word, /inta_jin/ [ئنتايين], "very" had three primes: an identity prime /inta_jin/ [ئنتايين], a transposed-letter prime /itna_jin/ [ئتنايين] (note that the letters ﺘ ["t"] and ﻨ ["n"] switched position within the same PAW), and a replacement-letter prime, /idʒsa_jin/ [ئجسايين] (note that the critical letters were replaced by ﺴ [the letter šīn, /s/] and ﺠ [the letter ǧīm, /dʒ/] within the same PAW). For the "different-ligation" word, */so_w_ʁa_t/* [سوۋغات], "gift," a similar set of three primes was used: an identity prime */so_w_ʁ̲a_t/* [سوۋغات], a transposed-letter prime */so_wʁ̲_a_t/* [سوغۋات] in which the ligation pattern varies, and a replacement-letter prime, /so_ʧd_a_t/, [سوچدات], in which the critical letters, for example, were replaced by ﭽ (the letter čīm, /ʧ/) and د) the letter dāl, /d/(and kept the same ligation pattern as the transposed-letter prime.

The mean frequencies of the target words in the "same-ligation" and "different-ligation" sets were 84.76 and 63.40 occurrences per million in the Uyghur word database (available at http://www.xjuit.biz/cn/), respectively. The mean number of letters of the target words was 6.25 and 6.23, respectively, and the mean number of orthographic neighbors of the target words (Coltheart's N) was 2.38 and 3.23, respectively (all $ts < 1$). Also, the frequency per million of the critical bigram was matched across the transposed-letter and replacement-letter priming conditions in the two sets of words ("same-ligation" set: 2483 vs. 2623; "different-ligation" set: 1990 vs. 1979; both $ts < 1$; note that, unsurprisingly, the identity condition had a higher frequency in the critical bigram: 5,485 and 4,489 in the same- and different-ligation sets, respectively, $p < .001$). All transposed-letter and replacement-letter primes were nonwords in Uyghur. The set of word targets and their corresponding primes is available at http://www.uv.es/mperea/Uyghur_ligation_priming.pdf.

We also created 102 nonword targets for the purposes of the lexical-decision task. The nonwords were orthographically legal in Uyghur but do not exist in the Uyghur lexicon. These nonwords were created using the same-ligation and different-ligation pattern and also had three different priming conditions (identity, transposed-letter, and replacement-letter).

Table 3
Mean Lexical Decision Times (in ms) and Percentage of Errors (in Parentheses) for Word and Nonword Targets in Experiment 1

	Identity	Transposed-letter	Replacement-letter
Words			
Same-ligation pattern	699 (7.5)	696 (9.2)	722 (10.4)
Different-ligation pattern	665 (7.3)	694 (7.4)	712 (9.0)
Nonwords			
Same-ligation pattern	793 (10.8)	795 (8.9)	802 (9.4)
Different-ligation pattern	783 (12.8)	775 (11.0)	797 (10.0)

Overall, there were 204 targets (102 words and 102 nonwords). We used a Latin Square design, creating three lists to counterbalance the target words across the three priming conditions (i.e., if a target stimulus was preceded by an identity prime in List 1, it was preceded by a transposed-letter prime in List 2, and it was preceded by a replacement-letter prime in List 3).

Procedure. Participants were tested individually in a quiet computer lab. The stimuli were presented using a windows-OS computer running DMDX (Forster & Forster, 2003). In each trial, a forward mask composed of hash marks (#####) was presented for 500 ms at the center of the CRT screen. This was immediately replaced by the prime stimulus for 50 ms in 48-pt Uyghur Tuz Tom (i.e., three refresh rates). Then the target word was immediately presented in 72-pt Uyghur Tuz Tom font until the participant responded or 2-s had passed.[1] Participants were instructed to press the "yes" button if the string of letters formed a real Uyghur word and to press the "no" button if the string of letters was not a word in Uyghur. They were asked to make this decision as fast and as accurately as possible. Participants were not informed of the presence of the primes. Twelve practice trials of the same characteristics as the experimental trials preceded the experiment. Each participant received a different randomized order of the trials.

Results and Discussion

Response times beyond two standard deviations from the participant's mean (4.2% of data) as well as errors were excluded from the latency analyses.[2] The mean RTs and error percentages from the by-subject analysis are shown in Table 3. For both the RTs and errors, a 2 (target type: same ligation pattern, different ligation pattern) × 3 (prime type: identity, transposed-letter, replacement-letter) × 3 (list: List 1, List 2, List 3) ANOVA was

[1] Previous ERP research using different sizes of masked primes and targets (30pt Roman script prime words and 44pt target words vs. 30pt Roman script prime words and 30pt target words; see Chauncey et al., 2008) has shown that the repetition priming effect was not modulated by the size of the prime/target words.

[2] Had we used another trimming procedure for the RT data (e.g., 2.5 standard deviations from the participant's mean), the pattern of findings would be the same as that reported here.

conducted for both subject and item means. List was included in the design as a factor to remove the error variance associated with the lists (see Pollatsek & Well, 1995). Separate analyses were conducted for word and nonword targets.

Word targets. The ANOVA on the RTs revealed a main effect of prime type, $F1(2,108) = 24.33$, $MSE = 1481$, $p < .001$; $F2(2,192) = 22.33$, $MSE = 1732$, $p < .001$, and an effect of type of target in the by-subjects analysis, $F1(1,54) = 6.78$, $MSE = 4587$, $p = .012$; $F2(1,96) = 2.33$, $MSE = 19412$, $p = .13$. More important, there was an interaction between the two factors, $F1(2,108) = 5.17$, $MSE = 1550$, $p = .007$; $F2(2,192) = 3.59$, $MSE = 1732$, $p = .029$. This interaction reflected an ID = TL < RL pattern for the same-ligation pairs: there was a negligible difference between the identity and transposed-letter conditions (699 vs. 696 ms, as in /inta_jin/-/inta_jin/ = /itna_jin/-/inta_jin/; both Fs < 1) and an advantage of the transposed-letter condition over the replacement-letter condition, 26 ms; $F1(1,54) = 13.90$, $MSE = 1443$, $p < .001$; $F2(1,48) = 15.39$, $MSE = 1746$, $p < .001$. In contrast, we found a ID < TL < RL pattern for different-ligation pairs: We found an advantage of the identity condition over the transposed-letter condition (29 ms, as in /so_w_ʁa_t/-/so_w_ʁa_t/ < /so_wʁ_a_t /-/so_w_ʁa_t/); $F1(1,54) = 18.42$, $MSE = 1276$, $p < .001$; $F2(1,48) = 10.42$, $MSE = 1769$, $p = .002$, and an advantage of the transposed-letter condition over the replacement-letter condition, 18 ms; $F1(1,54) = 6.99$, $MSE = 1393$, $p = .011$; $F2(1,48) = 6.77$, $MSE = 1612$, $p = .012$.

It is important to indicate that, when only considering the identity and the transposed-letter priming conditions, the interaction between prime type and target type was significant, $F1(1,54) = 10.42$, $MSE = 1424$, $p = .002$; $F2(1,96) = 7.01$, $MSE = 1744$, $p = .009$, whereas, when considering the transposed-letter and replacement-letter priming conditions, the interaction between prime type and target type did not approach significance, $F1 < 1$, $F2(1,96) = 1.06$.

The ANOVA on the error data revealed only a main effect of prime type, $F1(2,108) = 3.39$, $MSE = 44.1$, $p = .037$; $F2(2,192) = 3.81$, $MSE = 35,1$, $p = .024$, that reflected more error rates in the replacement-letter condition than in the identity condition (ps = .022 and .007 in the by-subjects and by-items analyses, respectively).

Nonword targets. None of the effects on the RTs for the nonword targets was significant. The ANOVA on the error data reflected only a main effect of prime type in the by-subjects analysis, $F1(2,108) = 3.25$, $MSE = 50.9$, $p = .043$, $F2(2,192) = 2.69$, $MSE = 37.6$, $p = .071$.

The current experiment revealed that word identification times to a target word were similar when preceded by an identity prime and when preceded by a transposed-letter prime that kept the same ligation pattern as the target word (/inta_jin/-/inta_jin/ = /itna_jin/-/inta_jin/, ئىنتايىن - ئىنتايىن = ئىتنايىن - ئىنتايىن), whereas there was a sizable and significant advantage of the identity over transposed-letter condition when the transposed-letter prime did not keep the same ligation pattern as the target word (/so_w_ʁa_t/-/so_w_ʁa_t/ < /so_wʁ_a_t /-/so_w_ʁa_t/, سوۋغات - سوۋغات < سوغۋات - سوۋغات). This extends the findings of Friedmann and Haddad-Hanna (2012) and Yakup et al. (2014) to a paradigm that taps the earliest stages of word processing.

A second finding was that the magnitude of the transposed-letter effect, compared with the replacement-letter condition, was greater in the same-ligation words than in the different-ligation words, although the difference was not significant (26 ms vs. 18 ms, respectively). It should be noted that the RL condition varied across same- and different-ligation words. In the same-ligation words, the RL prime keeps the same ligation pattern as the target word (e.g., /idʒsa_jin/ is the replacement-letter prime of the word /inta_jin/, and it keeps the ligation pattern as the transposed-letter prime /itna_jin/). However, in the different-ligation words, the RL prime does not keep the same ligation pattern as the target word (e.g., /so_ʧd_a_t/ is the RL prime of the word /so_w_ʁa_t/, because it keeps the ligation pattern as the transposed-letter prime /so_ʁw_a_t/).

Importantly, this distinction shows up in the present data with a greater difference between the ID and the RL conditions for different-ligation pairs than for same-ligation pairs (47 vs. 23 ms; i.e., the advantage of /inta_jin/ -/inta_jin/ over /idʒsa_jin/ -/inta_jin/ was greater than the advantage of /so_w_ʁa_t /-/so_w_ʁa_t/ over /so_ʧd_a_t/-/so_w_ʁa_t/). This pattern of data suggests that the ligation pattern may play a role when processing not only letter position but also letter identity in the Arabic script. As indicated in the Introduction, if one assumes the existence of a layer of PAWs between the letter level and whole-word level, the word /inta_jin/ ئىنتايىن would active *i-n-t-a-j-i-n* at the letter level, *inta-jin* at the "graphemic chunk" level, and *intajin* at the word level. Therefore, the prime /idʒsa_jin/ would be orthographically closer to the word /inta_jin/ than a prime such as /ir_sa_jin/. What we should note here is that Perea, Abu Mallouh, and Carreiras (2013, Experiment 1) found that, for pairs that shared the consonantal root with the target in Arabic, word identification times were slightly faster (a nonsignificant 6 ms effect) when the nonword prime shared the ligation pattern with the target (كتاب - كتزب ; ktz_b - ktA_b) than when it did not (كتاب - كتخب - ktxb-ktA_b; the root is *ktb*). However, this null result should be taken with some caution because of the constricted "root+word pattern" of Semitic languages (e.g., Arabic, Hebrew), in which morphological priming is very robust (see Velan & Frost, 2011) thus obscuring the potential impact of the ligation pattern.

The goal of Experiment 2 therefore was to examine whether the ligation pattern plays a role using two-letter replacement nonword primes. Specifically, we created two RL nonword primes for each target word, one that kept the ligation pattern as the target word (e.g., /idʒsa_jin/ ئىجسايىن for the target word /inta_jin/ ئىنتايىن ; /so_d_ʧa_t/ سودچات for the target word /so_w_ʁa_t/ سوۋغات) and another one that did not keep the same ligation pattern (e.g., /ir_sa_jin/ ئىرسايىن for the target word /inta_jin/; /so_ʧd_a_t/ سوچدات for the target word /so_w_ʁa_t/ سوۋغات). For comparison purposes with Experiment 1, an identity priming condition was also included.

The predictions are clear. If the ligation pattern plays a role during visual-word recognition in the Arabic script (e.g., in terms of a PAW layer between the letter and whole-word layers), word identification times of target words should be faster when preceded by a prime that keeps the same ligation pattern (i.e., the same PAW structure, as in /idʒsa_jin/-/inta_jin) than when preceded by a prime that does not keep the same ligation pattern (i.e., different PAW structure), as in /ir_sa_jin/-/inta_jin/. Note that this effect should be independent of the type of target (the "same-ligation" set and the "different-ligation" set). This outcome, using a within-item manipulation, would counter concerns that the data from the RL conditions in Experiment 1 are due to unique characteristics of the two sets of targets—note that, across conditions, word responses in the different-ligation set were slightly faster (around 15 ms) than the word responses in the same-ligation set, although these differences were not generalizable by items.

Experiment 2

Method

Participants. Forty-eight undergraduate students from Xinjiang University took part voluntarily in the experiment. All of them were native speakers of Uyghur and had normal/corrected-to-normal vision.

Materials. We used the target stimuli from Experiment 1 (102 words and 102 nonwords). Each target word was preceded by a prime that is: (a) the same as the target word (Identity condition); (b) the same as the target except for the replacement of two internal adjacent letters that kept the same ligation pattern as the target word (same-ligation RL condition; e.g., /idʒsa_jin/-/inta_jin/; /so_d_ʧa_t/-/so_w_ʁa_t/); and (c) the same as the target except for the replacement of two internal adjacent letters that did not keep the same ligation pattern as the target word (different-ligation RL condition; e.g., ., /ir_sa_jin/ for the target word /inta_jin/; /so_ʧd_a_t/ for the target word /so_w_ʁa_t/). The frequency per million of the critical bigram was matched across the two replacement-letter priming conditions (same ligation pattern RL primes = 1922; different ligation pattern RL primes = 1808; $t <$ 1). The set of word targets and their corresponding primes is available at http://www.uv.es/mperea/Uyghur_ligation_priming.pdf.

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

Results and Discussion

Response times beyond two standard deviations from the participant's mean (4.3% of the data) as well as errors were excluded from the reaction time (RT) analyses. The mean RTs and error percentages from the by-subject analysis are shown in Table 4. For both the RTs and errors, a 2 (target type: same ligation, different ligation) × 3 (prime type: identity, same-ligation pattern RL, different-ligation pattern RL) × 3 (list: List 1, List 2, List 3) ANOVA was conducted for both subject and item means. Separate analyses were conducted for word and nonword targets.

Table 4
Mean Lexical Decision Times (in ms) and Percentage of Errors (in Parentheses) for Word and Nonword Targets in Experiment 2

	Identity	Same-ligation Replacement-letter	Different-ligation Replacement-letter
Words			
Same-ligation pattern	702 (8.7)	729 (12.5)	747 (10.8)
Different-ligation pattern	684 (4.9)	712 (7.0)	730 (9.3)
Nonwords			
Same-ligation pattern	855 (14.7)	856 (14.6)	853 (13.1)
Different-ligation pattern	847 (16.1)	842 (15.3)	839 (15.2)

Word targets. The ANOVA on the RTs revealed a main effect of prime type, $F1(2,90) = 25.90$, $MSE = 1954$, $p < .001$; $F2(2,192) = 26.42$, $MSE = 2177$, $p < .001$, that did not interact with target type (both Fs < 1). This effect of prime type reflected an advantage of the same ligation pattern RL condition over the different ligation pattern RL condition, 18 ms; $F1(1,45) = 7.02$, $MSE = 2144$, $p = .011$; $F2(1,96) = 6.21$, $MSE = 2333$, $p = .014$, as well as an identity priming effect (i.e., an advantage of the identity condition over the two RL conditions, both $ps < .001$). The main effect of target type was significant in the analysis by subjects, $F1(1,45) = 10.47$, $MSE = 2155$, $p = .002$; $F2(1,96) = 3.70$, $MSE = 14716$, $p = .057$.

The ANOVA on the error data reflected a main effect of prime type, $F1(2,90) = 8.98$, $MSE = 34.3$, $p < .001$; $F2(2,192) = 5.93$, $MSE = 55.3$, $p = .003$, which did not interact with the effect of target type, $F1(2,90) = 2.36$, $MSE = 41.8$, $p = .099$; $F2(2,192) = 1.89$, $MSE = 55.3$, $p = .15$. This reflected fewer errors in the identity condition than in the two replacement-letter conditions (all $ps < .005$), whereas there were no differences across the two replacement-letter conditions (both $ps > .73$). The effect of target type was significant in the analysis by subjects, $F1(1,45) = 22.50$, $MSE = 41.3$, $p < .001$; $F2(1,96) = 2.55$, $MSE = 386.7$, $p = .11$.

Nonword targets. The ANOVA on the RTs reflected only an effect of target type in the analysis by subjects, $F1(1,45) = 5.06$, $MSE = 2169$, $p = .030$; $F2 < 1$. None of the effects on the error data was significant (all $ps > .12$).

The results of the current experiment are clear. The critical finding was that word identification times were, on average, 18 ms faster when the RL prime kept the same ligation pattern as the target word than when it did not (e.g., /iʤsa_jin/-/inta_jin/ faster than /ir_sa_jin/- /inta_jin/). Furthermore, this advantage was virtually the same magnitude for the two sets of words (i.e., "same ligation" and "different ligation" words): /iʤsa_jin/-/inta_jin/ faster than /ir_sa_jin/- /inta_jin/ and /so_d_ʧa_t/-/so_w_ʁa_t/ faster than /so_ʧd_a_t/-/so_w_ʁa_t/, thus ruling out an interpretation of the data from Experiment 1 in terms of uncontrolled characteristics of the target stimuli and instead suggesting an unambiguous advantage of same ligation patterns.

Moreover, if we examine the repetition priming effect compared to the replacement-letter conditions using the criteria from Experiment 1 (i.e., the different ligation pattern RL prime for the "different ligation" words and the same ligation pattern RL prime for the "same ligation" words), the size of the repetition priming effect was 46 ms and 27 ms, respectively. This is remarkably similar to the magnitude of the effects obtained in Experiment 1: 47 ms and 23 ms, respectively.

General Discussion

Computational models of visual-word recognition have primarily focused on the processing of English and other languages that employ the Roman script. The present masked priming experiments examined how letter identity/position is coded during the early stages of word processing in an agglutinative language (Uyghur) that is written in a semicursive script (Arabic). Both experiments show consistent contributions of same-ligation patterns in early processing. First, transposed-letter primes were as effective as identity primes when the letter transposition in the prime kept the same ligation pattern as the target word (e.g.,

/inta_jin/-/inta_jin/ = /itna_jin/-/inta_jin/), but not when the transposed-letter prime didn't keep the ligation pattern (e.g., (/so_w_ʁa_t/-/so_w_ʁa_t/] < /so_wʁ_a_t /-/so_w_ʁa_t/). Second, replacement-letter primes were more effective when they kept the same ligation pattern as the target word than when they did not (e.g., /so_d_ʧa_t/-/so_w_ʁa_t/ faster than /so_ʧd_a_t/-/so_w_ʁa_t/).

Are the Obtained Effects Due to Visual Similarity?

In the introduction, we indicated that evidence in the Roman script has shown that word responses in the masked priming lexical-decision task are generated on the basis of abstract codes rather than on visual similarity (e.g., the word recognition times to crash-CRASH vs. CRASH-CRASH [or even crash-CRASH vs. cRaSh-CRASH] are essentially identical; see Forster, 1998; Jacobs et al., 1995; Perea et al., 2014, 2015; see also Pylkkänen & Okano, 2010, for similar evidence from repetition priming of Hiragana-Katakana vs. Katakana-Katakana words). Indeed, when examining the ERP components of masked repetition priming for words (e.g., case-mismatched vs. case-matched identity primes: crash-CRASH vs. CRASH-CRASH), there are some differences between mismatched-case and matched-case identity pairs in early components related to visual processing (N/P150); however, these differences quickly vanish in components associated with orthographic/lexical/semantic processing (N250 and N400; Vergara-Martínez, Gomez, Jiménez, & Perea, 2015; see also Chauncey, Holcomb, & Grainger, 2008, for a similar N/P150 vs. N250 dissociation when manipulating variations in size and font between prime and target). Importantly, these findings are in agreement with the predictions of neural accounts of letter/word recognition (Dehaene, Cohen, Sigman, & Vinckier, 2005; Grainger, Rey, & Dufau, 2008), in which visual factors (e.g., compare crash-CRASH with CRASH-CRASH) only have an influence in the very earliest moments of letter/word processing.

However, one could argue that visual similarity could play a greater role in a semicursive script (Arabic) than in the Roman script. To examine the potential role of visual similarity in the obtained priming effects, we obtained visual similarity ratings for all the replacement-letter pairs of Experiment 2 (i.e., 204 pairs: 102 nonword-word pairs with same-ligation primes and 102 nonword-word pairs with different-ligation primes). Twelve students at the University of Valencia (Spain) rated these pairs on a 1–7 Likert scale (1 = *completely dissimilar*; 7 = *completely similar*). None of them had any knowledge of the Arabic script, so that the rating was based on visual elements and not on abstract letter processing (see Perea et al., 2013, for a similar procedure). Unsurprisingly, same-ligation pairs were judged as more visually similar than different-ligation pairs (4.67 vs. 4.256, respectively, $p = .002$ in the by-subjects analyses and $p < .001$ in the by-items analyses). Then, for each pair of stimuli, we computed the response time differences between the two replacement-letter conditions (different-ligation pairs minus same-ligation pairs) and the difference between the visual similarity ratings for these pairs—again, different-ligation pairs minus same-ligation pairs. The Pearson coefficient between these two variables was negligible ($r = -0.03$). This is also consistent with the lack of evidence for a role of visual similarity in the Yakup et al. (2014) RSVP experiment with same- versus different-ligation pairs. While we acknowledge that this is a post hoc analysis that needs to be taken with some caution, these data suggest that lexical decision responses in masked priming experiments occur at an orthographic/lexical level of representation and not as a function of visual similarity between prime and target.[3]

Letter Identity and Letter Position in Semicursive Scripts

The present findings have a number of implications for models of visual-word recognition. If letter identity and letter position in Arabic were encoded as in the Roman script, then one would have expected to find a similar amount of masked priming regardless of whether the pairs share the ligation pattern or not. For instance, the word /inta_jin/ would be decomposed at the letter level as *i-n-t-a-j-i-n*. Therefore, the same-ligation prime /iʤsa_jin/ (i-ʤ-s-a-j-in) and the different-ligation prime /ir_sa_jin/ (i-r-s-a-j-in) would be perceptually similar to their base words. However, /iʤsa_jin/ was a more effective prime of the target word /inta_jin/ than the prime /ir_sa_jin/ (Experiment 2). To explain these data, one could argue that there is a layer of PAWs between the letter level and the word level, as suggested by Belaïd and Choisy (2006). While the flexible orthographic coding schemes that have been proposed for the Roman alphabet do not assign a role for PAWs—as they are absent in the Roman alphabet—these models do differentially code letter position. In particular, these models assume that letter position is coded more precisely as an external letter than as an internal letter (see Cox, Kachergis, Recchia, & Jones, 2011; Davis, 2010, for discussion). This external-letter versus internal-letter marker in the Roman alphabet explains why jumbled words in which the internal letters are transposed are orthographically closer to the target word than jumbled words in which an external letter is transposed (e.g., *jugde-JUDGE* is orthographically closer than *ujdge-JUDGE*). In the case of the Arabic script, an analogous mechanism may be at work at the PAW level with respect to letter identity/position. Thus, external letters in a PAW may be coded more precisely than the internal letters in a PAW, and this can be used to help processing the identity/order of the letters that constitute the words in Arabic script.

Furthermore, we must keep in mind that information concerning letter position in a PAW is marked in Arabic: Each letter has an allograph for initial, middle, and final positions within a PAW, together with the allograph that marks an isolated position (see Table 1). Let's first consider the effect on letter identity. For the

[3] One might argue that the presence of masked priming effects in a lexical decision task with "leet" words (i.e., "4" as a replacement of "A" in M4T3RIAL; e.g., M4T3RIAL-MATERIAL < M6T5RIAL-MATERIAL; see Perea, Duñabeitia, & Carreiras, 2008) contradicts the idea that visual similarity does not play a role in masked priming. However, as Kinoshita, Robidoux, Mills, and Norris (2014) demonstrated, when using letter replacements, cross-case visually similar pairs produce comparable response times (e.g., MHTERIAL-material; note that H resembles the letter A) as cross-case visually dissimilar pairs (e.g., MUTERIUL-material). To explain this dissociation, Kinoshita et al. (2014) argued that in a masked priming lexical decision task, the visually similar digit 4 in the leet prime M4TERI4L provides evidence in favor that it is the letter A (i.e., in a lexical decision task, the stimuli cannot be digits), thus explaining "leet" priming effects. In contrast, the visually similar letter H (instead of A) in the prime MHTERIHL is not effective because it provides evidence in favor of the letter H, not of the letter A.

same-ligation pair /idʒsa_jin/-/inta_jin/, the difference occurs in two middle letters of the initial PAW, whereas for the different-ligation pair /ir_sa_jin/-/inta_jin/ the difference not only occurs in the number of PAWs (two vs. three, respectively), but also in that the letters "r" and "s" in one of the pairs are external letters from different PAWs while the letters "n" and "t" of the other pair are in middle positions of the same PAW. Therefore, one would predict that the orthographic codes of idʒsa_jin/-/inta_jin/ are more similar than the orthographic codes of /ir_sa_jin/-/inta_jin/, as actually occurs (Experiment 2). Let's now consider the coding of letter position. The pair /itna_jin/-/inta_jin/ shares the same PAW skeleton, and the only difference is in two middle letters ("n" and "t" vs. "t" and "n") of the initial PAW. This makes these two stimuli very similar perceptually, and indeed Experiment 1 revealed that the masked transposed-letter prime /itna_jin/ is as effective as the identity prime /inta_jin/. In contrast, the letter forms in the different-ligation pair /so_wʁ_a_t /-/so_w_ʁa_t/ are different (i.e., "w" is in an initial position in one of the pairs, whereas it is in isolated position in the other pair; "ʁ" is in final position in one of the pairs and it is in initial position in the other pairs). Thus, the masked prime /so_wʁ_a_t/may be a less effective prime of /so_w_ʁa_t/ than the identity prime /so_w_ʁa_t/, as actually occurs (Experiment 1; see also Friedmann & Hadda-Hanna, 2012; Yakup et al., 2014, for a similar finding using unmasked words).

Implications for Modeling Visual Word Recognition in Semicursive Scripts

How are the present data accommodated within current models of letter coding? Consider one of the most influential theories of letter position coding, the family of open-bigram models (see Grainger & van Heuven, 2003; Whitney, 1999). In these models, upon presentation of a jumbled word like *JUGDE*, a set of "open bigrams" would be activated (*JU-JG-JD-JE-UG-UD-UE-GD-GE-DE*). Given that the vast majority of open bigrams are shared with its base word *JUDGE* (the exceptions are the open-bigrams *GD/DG*), *JUDGE* and *JUGDE* would be very similar in terms of activated bigrams, thus providing an explanation why *JUGDE* can be easily misperceived as *JUDGE*. Clearly, if open bigrams were considered purely as abstract units with no PAW information, the transposed-letter (or replacement-letter) primes in the different-ligation versus same-ligation set in the present experiments would activate exactly the same set of open-bigrams in common with their corresponding base words. However, the present results do not show this pattern, with significant differences observed between same-ligation and different-ligation primes. Therefore, the open-bigram model, without modification, cannot capture the present data in which identification times are most similar when prime and target keep the ligation pattern as compared with when prime and target do not. One option to accommodate the present findings is to assume that open bigrams are weighted depending on: (a) whether or not they form part of the same PAW; or (b) whether or not the letters share the same letter position information in the PAW (initial, middle, final, isolated)—the current experiments were not designed to separate these two explanations. As a result, the degree of orthographic similarity would be greater for orthographically related pairs that share the ligation pattern (e.g., */itna_jin/* ئىتنايىن and */inta_jin/* ئىنتايىن) than for the pairs that do not share the ligation pattern (e.g., */so_w_ʁa_t/* سوۋغات and */so_wʁ_a_t/* سوغۋات). This would be the case not only in letter position coding (Experiment 1), but it would also be the case in letter identity coding, as shown in Experiment 2 from the differences between the two replacement-letter conditions that keep the same ligation pattern or do not (i.e., /idʒsa_jin/-/inta_jin/ is more similar than /ir_sa_jin/- /inta_jin/).

Other models assume that letter position coding is best described as a perceptual process not unlike other forms of object position coding. Notably, the overlap model (Gomez et al., 2008) and the noisy-slot Bayesian reader model (Norris et al., 2010) assume that object positions can be best understood as overlapping fields instead of discrete points. These models can account for the present data through two mechanisms: (a) the physical distance between the transposed letters is smaller in the case of transposed-letter primes in which the transposition occurs in same-ligation pairs (e.g., /itna_jin/-/inta_jin/, ئىنتايىن - ئىتنايىن) than in transposed-letter primes in which the transposition occurs in different-ligation pairs (e.g., /so_ʁw_a_t/-/so_w_ʁa_t/, سوۋغات- سوغۋات); and (b) the blank-space itself might be perceived as an object in a location, so transpositions/replacements across PAWs are not strictly speaking adjacent, as in /..ʁw[space]../-/..[space]w[space]ʁ../. Therefore, the perceptual overlap between a target word and its transposed-letter or replacement-letter counterpart is greater when the ligation pattern is shared. Finally, the LTRS model (Adelman, 2011) assumes the existence of approximate positional information in the early stages of processing (i.e., as the overlap model), but it also assumes the activation of several types of representational units (e.g., open bigrams, adjacent bigrams and nonadjacent bigrams; i.e., as open bigram models). Therefore, as in the models described above, the LTRS model can accommodate the present data by assuming that pairs of stimuli in Arabic script that share the ligation pattern would be encoded more similarly and, hence, produce stronger masked priming effects than the pairs of stimuli that do not share the ligation pattern.

Another leading model of visual word recognition is the spatial coding model (Davis, 2010). In this model, the words CALM and CLAM share the same set of letter representations. Given that letter position in the model is coded "by the pattern of temporary values that are dynamically assigned (tagged) to these letters" (Davis, 2010, p. 716), for the word CALM, C would be assigned the highest value, A the second value, L the third value, and finally M would be assigned the lowest value. The spatial pattern of CLAM would differ from CALM in the values of the letter nodes corresponding to the second and third positions. One important feature of the spatial coding model is that the initial and final letters are explicitly marked—this explains why external letters is coded more accurately than internal letters in the Roman script. If we assume that, when reading in Arabic script, there are markers for the initial and final letters in each PAW, the spatial pattern used to code two stimuli is more similar when these share the ligation pattern (e.g., the transposed-letter pair */itna_jin/-/inta_jin/*) than when they do not share the ligation pattern (e.g., */so_w_ʁa_t/-/so_wʁ_a_t/*). A parallel argument applies to the case of replacement-letter pairs (e.g., the spatial pattern of the pair /idʒsa_jin/-/inta_jin/ is more similar than the spatial pattern of the pair ir_sa_jin/- /inta_jin/).

Conclusions

The present masked priming experiments demonstrate that, in the early stages of word processing, the manner in which letters are encoded in Arabic is modulated by the ligation pattern of the words, possible via the activation of a layer of PAWs. More research is necessary to further specify the details of a wide-ranging orthographic coding scheme that can successfully and simultaneously deal with Roman and Arabic scripts.

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