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BRIEF REPORT

How is letter position coding attained in scripts with position-dependent allography?

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Abstract We examined how letter position coding is achieved in a script (Arabic) in which the different letter forms (i.e., allographs) may vary depending on their position within the letter string (e.g., compare the same-ligation pair ئىتنايىن and ئىنتايىن vs. the different-ligation pair سوۋغات and سوغۋات). To that end, we conducted an experiment in Uyghur, an agglutinative language from the Turkic family that employs an Arabic-based script in which both consonants and vowels are explicitly written. Participants had to reproduce the correct word forms in rapid serial visual presentation sentences that either contained jumbled words (with the same ligation or different ligation) or were intact. The results revealed that readers had more difficulty correctly reporting the target words in the jumbled sentences when the letter transposition involved changes in the ligation pattern, thus demonstrating that position-dependent allography affects letter position coding. This finding poses constraints to a universal model of letter position encoding.

Keywords Letter position · Lexical access · Word recognition

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The question of how letter identity and letter position are encoded during the recognition of printed words in reading has intrigued researchers for more than 50 years (Bruner & O'Dowd, 1958). A large body of evidence in very different paradigms and scripts (e.g., Roman, Hebrew, Arabic, Japanese kana, Thai, or Korean Hangul) has demonstrated that letter position coding is highly flexible (Frost, 2012). An example of such flexibility is that when presented with sentences with jumbled [transposed-letter] words (e.g., "the jugde asked his brohter for the truth"), readers can readily reproduce the correct words with only a small cost in reading speed (Rayner, White, Johnson, & Liversedge, 2006).

The goal of the present experiment was to examine the role of position-dependent allographs in letter position coding. Allographs are the diverse forms in which a grapheme can be written (e.g., a, *a*, 𝓐, and A are all allographs of the letter "a"). In the Roman alphabet, all neural hierarchical accounts of letter/word processing assume a mechanism in which, at the lower levels, detectors respond to case-specific representations (e.g., the "A" detector responds to 𝓐 or A, but not to a or *a*), whereas, higher in the hierarchy, a set of "abstract letter detectors" respond to case-independent representations (the "A" detector responds equally to a, *a*, 𝓐, and A; Dehaene, Cohen, Sigman, & Vinckier, 2005; Grainger, Rey, & Dufau, 2008). But the story may be more intricate. Although allographs in the Roman script are position-independent, in some scripts the visual appearance of letters may vary substantially, depending on their position in the word. That is, these allographs contain positional information of the letter within the string (e.g., in classical Greek, the letter sigma is written ς at the end of a word and σ in other positions). The richest script in terms of position-dependent allography is the Arabic script used in a variety of languages (Arabic, Kurdish, Pashto, Persian, Urdu, and Uyghur, among others), which is read from right to left. Leaving aside the lack of a lowercase/uppercase distinction, the Arabic script has two important features. First, it is a semicursive script in which some of the letters can be connected to the adjacent letter, forming "graphemic chunks" (Perea, Abu Mallouh, & Carreiras, 2013). For instance, the word مسن [*aged*, or *msr*, using the Buckwalter transliteration] has the three letters connected (i.e., just one graphemic chunk, which coincides with the word); the word رقبة [*neck*, *rqbh*] is composed of two graphemic chunks (قبة and ر); whereas ورد [*roses*, *wrd*] has all letters separated (i.e., three graphemic chunks). Second, the visual form of each letter depends on its position in each graphemic chunk—and for a few letters, the different allographs may differ substantially. For instance, the letter ك [kāf, *k*] has four different forms: as a beginning letter connected to the second letter, كـ; as a middle letter connected on both sides, ـكـ; as a final letter connected to the second-to-last letter, ـك; and as an isolated (nonconnected) letter, ك (see Perea et al., 2013, for an illustration).

What are the implications of the presence of position-dependent allographs for letter position coding? Transposed-letter neighbors may share the same graphemic chunk (e.g., the words تمهل [*slowed*, *tmhl*] and تهمل [*neglect*, *thml*]) or may not (e.g., the words شراع [*sail*, *$rAE*] and شارع [*street*, *$ArE*]). In the first set, the transposed letters in تمهل and تهمل share the same position-dependent allographs (i.e., both middle position allographs), whereas in the second set, the transposed letters in شراع and شارع do not share the same position-dependent allographs. If position-dependent allography plays a role in letter position coding, then تمهل and تهمل should be orthographically more similar than شراع and شارع. Of particular interest here is a recent naming study by Friedmann and Haddad-Hanna (2012) with three native speakers of Arabic who suffered from "letter position dyslexia." Friedmann and Haddad-Hanna found that these participants made a much larger number of letter transposition errors when the presented word shared the same structure of the graphemic chunk (i.e., the "ligation pattern") with a transposed-letter competitor (85 % of errors; e.g., تمهل [*slowed*, *tmhl*] was frequently misread as تهمل [*neglect*, *thml*]), but not when the ligation pattern of the transposed-letter neighbor was different (ranging from 1 % to 16 %; e.g., جهاز [*device*, *jhAz*] was not read as جاهز [*ready*, *jAhz*]). This was the case, regardless of whether there was a noticeable change in letter form of the allographs (e.g., the position-dependent allographs of the transposed letters in شراع and شارع look visually similar), thus suggesting that the detectors of "abstract letter units" in Arabic may contain position-dependent information. Similarly, Kinoshita, Norris, and Siegelman (2012), after describing the data from Friedmann and Haddad-Hanna, claimed that for "position-dependent allographs, the letters transposed in position are effectively 'wrong letters'" and that this highlights "the need to take account of position-dependent allography in studying letter position coding in Arabic" (pp. 1303–1304).

One potential limitation of the Friedmann and Haddad-Hanna (2012) findings is that this pattern of data could be restricted to (or be more salient in) a population of participants with dyslexia rather than in the population of adult skilled readers. To examine the generality of their conclusions, it was critical to examine this issue with skilled adult readers (i.e., the population of reference in most psycholinguistic studies). Although the seemingly straightforward decision would be to similarly employ the Arabic language, it is important to mention that Arabic has a rigid morphological structure (consonantal root + word pattern; see Frost, 2012; Perea, Abu Mallouh, & Carreiras, 2010) that makes it difficult to create well-controlled experimental stimuli. Furthermore, Arabic orthography does not present (full) vowel information (e.g., *ktb* would refer to the word *kataba*), which implies that a single letter transposition may involve greater changes than the parallel transposed-letter manipulation in English (or in other Indo-European languages). For these reasons, we opted for running the experiment in Uyghur, a language in which, although it uses a Persian–Arabic-based script, all 24 consonants and eight vowels are explicitly written. Uyghur is the official language in the Xinjiang Uyghur Autonomous Region of China. Importantly, Uyghur is an agglutinative language of the family of the Turkic languages (i.e., non-Semitic) in which suffixes (e.g., personal case, number, tense, aspect) are added linearly to the word stem—as in other agglutinative languages like Basque or Finnish (see Duñabeitia, Perea, & Carreiras, 2007; Perea & Carreiras, 2006, for evidence of transposed-letter effects in Basque). For example, in the Uyghur word /øjiŋizge(øj-iŋiz-ge, literally 'house-your-to', *to your house*), the noun *house* occurs first, and the modifying elements are attached directly to it (see Engesæth, Yakup, & Dwyer, 2009, for a brief introduction to Uyghur orthography/morphology).

In the present experiment, we created two types of transposed-letter pseudowords in Uyghur. On the one hand, we created a set of "same-ligation" pseudowords by transposing two adjacent internal letters of a Uyghur word while keeping invariable the ligation pattern—and, consequently, the letter position information of the critical letters. One example of the same-ligation pattern is the transposed-letter pseudoword [ئتنايىن] /itnajin/, which was created from the word [ئنتايىن] [intajin, *very*]. Note that the letters /t/ and /n/ are represented in the two cases by the middle allograph forms (and ـتـ) in the same graphemic chunk. On the other hand, we created a set of "different-ligation" pseudowords by transposing two adjacent internal letters that varied the original ligation pattern. One example of the different-ligation pattern is the transposed-letter pseudoword [سوغۋات] /so_ʁw_a_t/, which was created from the word [سوۋغات] /so_w_ʁa t/, *gift*. We have added underlined bars in the phonetic rendering to illustrate the changes in the ligation pattern. In the transposed-letter pseudoword, the allographs “ʁ” and “w” correspond to the initial and final allograph forms within the same graphemic chunk (i.e., غۋ), whereas in the original word they correspond to an isolated allograph form (ۋ) and the initial position (غ) of another graphemic chunk.

For all “same-ligation” and “different-ligation” pseudowords, the letter transpositions involved two adjacent consonant letters within the stem, the reasons being that between-morpheme transpositions in polymorphemic words may diminish the size of transposed-letter effects (Christianson, Johnson, & Rayner, 2005) and that transposed-letter effects are greater for consonant than for vowel transpositions (Perea & Lupker, 2004).

As in the experiments of Velan and Frost (2007; see also Perea, Gatt, Moret-Tatay, & Fabri, 2012; Velan & Frost, 2011), we employed a rapid serial visual presentation (RSVP) procedure. In this technique, sentences are rapidly presented on the screen on a word-by-word basis. Half of the presented sentences contained two jumbled words, whereas the other half of the sentences were presented intact. The participants’ task was to reproduce the sentences in written form following the final word of the sentence—with the correct spelling in the case of jumbled words. Prior studies have revealed that, when sentences are presented in English, the participants’ accuracy with the jumbled words is nearly as good as their accuracy with intact words (Velan & Frost, 2007, 2011; see also Perea et al., 2012), and the same pattern is observed in loan words in Hebrew (Velan & Frost, 2011) and Semitic words in Maltese (Perea et al., 2012), thus demonstrating the flexibility of letter position coding during reading. Importantly, however, when participants are presented with jumbled Hebrew words, performance is substantially worse with the jumbled words than with intact words (Velan & Frost, 2007). Velan and Frost concluded that this was because the transpositions in the consonantal root prevented the processing system from extracting the correct identification of the specific root morpheme, which is critical for lexical access in Hebrew.

Thus, the main goal of the present experiment was to examine the role of position-dependent allography in letter transposition effects in a language, Uyghur, that uses the Arabic script. Note that, at the level of letter identities, sizeable effects of masked (morphological) priming in Arabic have been reported in experiments that have not controlled for position-dependent allography (e.g., in pairs like كتاب–كتخب [ktxb–ktAb; the root is *ktb*]; Frost, Kugler, Deutsch, & Forster, 2005; Perea et al., 2010). If, as Friedmann and Haddad-Hanna (2012) claimed, position-dependent allography plays a role in letter transposition effects, the reading cost (i.e., the difference when reproducing the words in jumbled vs. intact sentences) should be greater for those sentences containing “different-ligation” jumbled words (e.g., سوۋغات and سوغۋات) than for those sentences containing “same-ligation” jumbled words (ئىنتايىن and ئىتنايىن). That is, similar to what happens with root transpositions in Semitic words relative to loan words, in Hebrew, participants should have more difficulty reproducing the target words in the case of different-ligation pseudowords than in the case of same-ligation pseudowords. Alternatively, if the locus of letter position coding is purely at an abstract level of representation, invariant to position-dependent letter information, participants should reproduce the jumbled words to similar degrees, independently of whether the jumbled words have the same ligation pattern as their base words or a different one.

Method

Participants

A group of 28 undergraduate students at Xinjiang University took part in the experiment. All of them had Uyghur as their mother tongue and Chinese as a second language, and all had normal (or corrected-to-normal) vision.

Materials

We created 20 sentences for the “same-ligation” set and 20 sentences for the “different-ligation” set. For each sentence, we included two target words (these were both same-ligation or different-ligation). These target words were located sentence medial, in neither the initial nor the final position of the sentence, and none of the target words were consecutive. Examples of each condition are given in Table 1. For both the same-ligation and the different-ligation conditions, the first sentence in the table is the intact sentence, and the second sentence has two jumbled target words created by transposing two adjacent internal letters. For these “jumbled-word” sentences, we transposed two adjacent consonants in the stems of the two target words (e.g., /intajin/ for /itnajin/, and /*sowʁat*/ for /*soʁwat*/). For the same-ligation sentences, the ligation was the same after the letter transposition, whereas for the different-ligation sentences, the ligation changed.

The grammatical structures of the “same-ligation” and “different-ligation” sentences were equivalent, and the mean frequencies of the target words in the same-ligation and different-ligation sets were 34.48 and 30.94 occurrences per million, respectively. These data were taken from the Uyghur word database (available at www.xjuit.biz/cn/). The mean numbers of letters of the target words were 7.40 and 7.22, respectively, and the mean numbers of orthographic neighbors of the target words were 2.63 and 3.05, respectively (all *t*s < 1). We created two lists in a Latin square manner, so that each participant was presented with ten sentences per condition (40 experimental sentences overall). Each experimental list

Table 1 Illustration of same-ligation and different-ligation sentences in the experiment

Same-Ligation Sentences						
بۇ هارۋكەش يېزا يوللرنى ئىنتايىن ياخشى بلىدۇ.					Intact sentence	
بۇ هاۋركەش يېزا يوللرنى ئىتنايىن ياخشى بلىدۇ.					Sentence with jumbled words	
Bu	harwikesh	yéza	yol-lar-ni	intayin	yaxshi	bil-idu
This	cartdriver	countryside	road-PL-ACC	extremely	good	know-3rd sg. PRE
This cart driver knows the countryside road extremely well.						
Different-Ligation Sentences						
بۇ بايرامدا چوڭ ئاپام بزگە سوۋغات بەردى.					Intact sentence	
بۇ باريامدا چوڭ ئاپام بزگە سوغۋات بەردى.					Sentence with jumbled words	
Bu	bayram-da	chong	apa-m	biz-ge	sowghat	ber-d-i
This	festival-LOC	big	mother-1st. POSS	we-DAT	gift	give-3rs PAST
In this festival, our grandmother gave us gift.						

included 20 intact sentences (ten for the same-ligation and ten for the different-ligation pattern) and 20 jumbled sentences (ten for the same-ligation and ten for the different-ligation pattern). In addition, if a sentence was shown in list A in an intact form, it was shown in list B in a jumbled form. Therefore, each participant saw only one condition of the target word, in either intact or jumbled form. The list of sentences is available at www.uv.es/mperea/Uyghur_RSVP.pdf and in the supplementary materials.

Procedure

Participants were tested individually. The sentences were presented using a computer running DMDX (Forster & Forster, 2003). The instructions were given orally and on the screen. Participants had to press the spacebar to start each trial. For each trial, every word in the sentence was presented for 200 ms at the center of the screen. Participants were asked to write down the sentence, or at least the words that they could reproduce, following the final word of each sentence. Participants were alerted that, in some sentences, the words would be jumbled, and they were asked to write down the correct spelling. The instruction and examples were given in Uyghur. Four practice sentences (one in each condition) preceded the 40 experimental sentences. The order of the experimental sentences was randomized for each participant.

Results

Similarly to the Velan and Frost (2007, 2011) experiments, we conducted a repeated measures analysis of variance (ANOVA) on the percentages of report of the target words for subjects (F_1) and items (F_2)—the factors were Type of Sentence (intact, jumbled) and Type of Transposition (same ligation, different ligation). Given that the dependent variable was binomial in origin (1 = *correct*, 0 = *incorrect*), and to back up the above-cited analyses, we also conducted linear mixed-model (LMM) effects using Type of Sentence and Type of Transposition as fixed-effects factors. The random effects were the intercepts for subjects and items, as well as the by-subjects and by-items random slopes for type of sentence (intact, jumbled). Likelihood ratio tests were used to obtain p values. The averages across subjects in each condition are shown in Table 2.

Overall, participants reproduced the target words more accurately in intact than in jumbled-word sentences [80.2 % vs. 70.8 %, respectively; $F_1(1, 27) = 9.91$, $MSE = 248.4$, $p = .004$; $F_2(1, 78) = 25.08$, $MSE = 140.2$, $p < .001$; LMM: $\chi^2(2) = 13.32$, $p = .001$]. More importantly, this effect was qualified by an interaction between the two factors [$F_1(1, 27) = 5.48$, $MSE = 106.0$, $p = .027$; $F_2(1, 78) = 5.92$, $MSE = 140.2$, $p = .017$; LMM: $\beta = 0.583$, $SE = 0.268$, $\chi^2(1) = 4.17$, $p = .04$, comparing the additive vs. the interaction model]: The reading cost of the jumbled words was larger for the different-ligation words (81.4 % vs. 67.5 %), $t_1(27) = 4.57$, $p < .001$; $t_2(39) = 3.12$, $p = .003$; LMM: $\beta = -0.806$, $SE = 0.243$, $\chi^2(1) = 8.99$, $p = .003$] than for the same-ligation words (78.9 % vs. 74.1 %),

Table 2 Percent report of target words (top) and of all words (bottom) in intact sentences and sentences with jumbled words

	Intact Sentences	Sentences With Jumbled Words
Target Words		
Same ligation	78.9 (12.7)	74.1 (13.1)
Different ligation	81.4 (14.1)	67.5 (16.1)
All Words		
Same ligation	86.6 (7.0)	84.3 (7.2)
Different ligation	85.7 (7.7)	82.6 (7.3)

Standard deviations are shown in parentheses

[$t_1(27) = 1.69$, $p = .102$; $t_2(39) = 2.22$, $p = .033$; LMM: $\beta = -0.484$, $SE = 0.218$, $\chi^2(1) = 2.92$, $p = .08$]. Finally, a breakdown of the error types (e.g., misspellings of the target word, failing to produce the target word, or failing to reproduce other words in the sentence) did not reveal any clear differences between the intact and jumbled sentences (e.g., out of the total of errors in the each category, the percentages of failing to produce the target word were 61.0 and 64.1 for the same-ligation sentences [intact, jumbled], and 70.2 and 69.8 for the different-ligation sentences [intact, jumbled]).

We also examined a second dependent variable, the overall percentages of correct report of all words (see Table 2, bottom), similar to the Velan and Frost (2007) experiment. In this case, the ANOVA revealed only a small (2.7 %) reading cost of the sentences with jumbled words [$F(1, 27) = 4.95$, $MSE = 200$, $p = .035$]. Note that this was slightly larger for the different-ligation sentences (3.1 %) than for the same-ligation sentences (2.3 %) but did not reach significance (interaction: $F < 1$). Thus, the reading cost of the jumbled words did not carry over to the other words in the RSVP sequence.

Discussion

Uyghur is an agglutinative language from the Turkic family that employs an Arabic–Persian-based script. Unlike Arabic, Uyghur does not have the strict "root + word" pattern constraints of Semitic languages, and it does not omit vowels in print. Thus, Uyghur provides an excellent window to examine whether position-dependent allography plays a role in letter position coding. Specifically, the research question was whether Uyghur readers, when reproducing jumbled words (relative to intact words) presented in RSVP sequences, would differ depending on whether or not the jumbled words shared a ligation pattern with their base words. Our results revealed that Uyghur readers had more difficulty in reporting the target words when the letter transposition involved changes (e.g., from [سوۋغات] / so_w_ʁa_t/ to [سوغۋات] /so_ʁw_a_t/) in the ligation pattern (from 81.4 % in the intact sentences to 67.5 % in the jumbled-word sentences) than when the letter transpositions did not involve changes (e.g., from [ئىنتايىن] /inta_jin/ to [ئىتنايىن] /itna_jin/) in the ligation pattern (from 78.9 % in the intact sentences to 74.1 % in the jumbled-word sentences). Importantly, unlike in the experiments with Hebrew words reported by Velan and Frost (2007, 2011), this reading cost did not carry over to the rest of the words in the RSVP sequence: The reading costs for all words were 3.1 % versus 2.3 % for the different-ligation and the same-ligation sentences, respectively.

The present data revealed that adult skilled readers use their knowledge of the position-dependent allographs to reproduce the appropriate jumbled word in rapidly presented sequences of words, so that the same-ligation transposed-letter pseudoword [ئىنتايىن] can be more easily reconstructed (as ئىتنايىن) than can the different-ligation transposed-letter pseudoword سوغۋات(as سوۋغات), generalizing the data from word-naming errors in three individuals with "letter position dyslexia" reported by Friedmann and Haddad-Hanna (2012). The present data on transposed-letter effects in Uyghur directly address current models of visual-word processing. These findings also have a methodological take-home message: Position-dependent allography should be considered in future experiments dealing with letter position coding in experiments using the Arabic script.

What is the nature of letter position coding (via letter transposition effects) in the Arabic reading system? If letter transposition effects arose only at an abstract identity level that is invariant to position-dependent letter information, there should be no influence of whether or not the position-specific allographs look similar. This hypothesis has been falsified in the present experiment: Participants can reproduce the target word more easily in same-ligation pairs (e.g., /itna_jin/ ئىتنايىن and /inta_jin/ ئىنتايىن) than in different-ligation pairs (e.g., /so_w_ʁa_t/ سوۋغات and /so_wʁ_a_t/ سوغۋات). A further question is whether letter transposition effects in Arabic script arise at a visual, retinotopic level (e.g., based on visual cues such as letter shape) or at an orthographic level at which position-dependent information from the word's constituent letters forms an integral part of the word representation, as was advocated by Friedmann and Haddad-Hanna (2012). To examine the visual letter-level option, we divided the 40 different-ligation jumbled words into visually similar and visually dissimilar position-specific allographs (26 vs. 14 words, in each case) and compared the transposed-letter effects across these categories. The size of the effect was slightly larger for the visually similar position-specific allographs (e.g., سوۋغات - سوغۋات; 83.5 % vs. 66.8 % accuracy in the intact and jumbled sentences, respectively) than for the visually different position-specific allographs (e.g., تۆۋپەھ - تۆۋھپە; 77.7 % vs. 68.9 % accuracy in the intact and jumbled sentences, respectively; interaction: $p = .21$). If anything, the greater visual similarity leads to a greater (not a lesser) reading cost. Although we acknowledge that this is a post-hoc analysis with an unbalanced set of words, it does suggest that visual letter shape may not be the key player in the effects that we obtained. Instead, it suggests that in scripts with letter position allography, although a word's graphemic representation may be invariant to irrelevant parameters, such as $^{\text{position}}$, size, or font, the specific allograph (i.e., whether the letters appears in the initial, middle, or final part of the graphemic chunks) forms an integral part of the word's graphemic representation, as was claimed by Friedmann and Haddad-Hanna (2012). Therefore, orthographic similarity contributes more in same-ligation pairs (i.e., transpositions of abstract letter identities that keep the same letter-position-dependent information; e.g., /itna_jin/ ئتنايين and /inta_jin/ ئنتايين) than in different-ligation pairs (e.g., /so_w_ ʁa_t/ سوۋغات and /so_wʁ_a_t/ سوغۋات). This hypothesis has a direct precursor in the Roman script. In the context of the processing of proper versus common names, Peressotti, Cubelli, and Job (2003) claimed that “the uppercase–lowercase distinction is abstract in nature since it is an intrinsic property of letters” (their “orthographic cue” hypothesis, p. 108). We believe that the same argument would apply to letter position allographs in Arabic.

Importantly, recent research has revealed similar identity-priming effects when manipulating letter case information in the Roman script and position-dependent allography in Arabic. Carreiras, Perea, and Abu Mallouh (2012) found masked repetition priming of similar magnitudes for visually different allographs (e.g., ع and ـعـ are allographs of the letter /ʾayn) and for visually similar allographs (ط and ط are allographs of /ṭāʾ), thus suggesting fast access to the abstract representations of the letters, as also happens with allographs such as d/D in the Roman script. Importantly, in an event-related potential experiment, Carreiras, Perea, Gil-López, Abu Mallouh, and Salillas (2013) replicated the behavioral findings of Carreiras et al. (2012) and revealed that the spatial distribution of the masked repetition priming effects with lowercase versus uppercase Latin letters and isolated versus middle-letter allographs in Arabic were similar. Furthermore, the spatial distribution of the repetition effect was modulated by prime–target visual similarity (ع/ـعـ vs. ط/ ط; d/D vs. c/C), even at a relatively late time window (P300). This is, again, consistent with the view that letter case information (Roman script; Peressotti et al., 2003) and letter position information (Arabic script; Friedmann & Haddad-Hanna, 2012) may form parts of a word’s long-term orthographic representation.

In sum, position-dependent allography modulates the magnitude of letter transposition effects of readers of Arabic script: Jumbled words in the different-ligation condition are less orthographically similar to their base words than are jumbled words in the same-ligation condition. Further research on the time courses of the encoding of letter position and letter identity with the Arabic script (in both Semitic [e.g., Arabic] and non-Semitic [e.g., Uyghur] languages) will be necessary in order to develop computational and neural models beyond Anglo-centric accounts that focus on the Roman script.

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