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The Impact of Text Orientation on Form Priming Effects in Four-Character Chinese Words

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Does visuospatial orientation influence repetition and transposed character (TC) priming effects in logographic scripts? According to perceptual learning accounts, the nature of orthographic (form) priming effects should be influenced by text orientation (Dehaene, Cohen, Sigman, & Vinckier, 2005; Grainger & Holcomb, 2009). In contrast, Witzel, Qiao, and Forster's (2011) abstract letter unit account argues that the mechanism responsible for such effects acts at a totally abstract orthographic level (i.e., the visuospatial orientation is irrelevant to the nature of the relevant orthographic code). The present experiments expanded this debate beyond alphabetic scripts and the syllabic Kana script used by Witzel et al. to a logographic script (Chinese). Experiment 1 showed masked repetition and TC priming effects with primes and targets presented in both the conventional left-to-right horizontal orientation and the vertical top-to-bottom orientation, replicating Witzel et al. Experiment 2 showed masked repetition and TC priming effects even when both the primes and targets were presented in the right-to-left orientation, a rare but existent text orientation in Chinese. In Experiment 3, the primes, but not the targets, were presented in the right-to-left orientation. Priming effects were again obtained regardless of the fact that the primes and targets appeared in different orientations. Experiment 4, which involved primes and targets presented in a completely novel bottom-to-top orientation, also produced a TC priming effect. These results support abstract letter/character unit accounts of form priming effects while failing to support perceptual learning accounts.

Keywords: form priming, text orientations, masked priming, lexical decision

How do people successfully code letter identity and letter position information in a presented word? One approach to this issue involves proposing a "channel specific" coding scheme, which is based on the idea that a letter's specific position is directly coded, even before its identity is coded. The multiple read-out model (Grainger & Jacobs, 1996) and the interactive-activation model (McClelland & Rumelhart, 1981) are examples of models making this type of assumption. What is most relevant to the present discussion is that models making this assumption predict that transposed letter (TL) nonwords (e.g., jugde) are no more similar to their base words (i.e., JUDGE) than are substituted letter (SL) nonwords (e.g., jupte) and, therefore, the two types of nonwords should produce equivalent priming effects for their base word in masked priming experiments. More recent behavioral (e.g., Lété & Fayol, 2013; Perea & Lupker, 2003a, 2003b, 2004; Perea, Winskel, & Gómez, 2018), and event-related potential (ERP) results (e.g., Ktori, Kingma, Hannagan, Holcomb, & Grainger, 2014; Vergara-Martínez, Perea, Gómez, & Swaab, 2013), however, have failed to support this prediction. That is, many studies have shown that TL nonwords appear to be considerably more similar to their base words than are SL nonwords. For example, Perea and Lupker (2003a), among others, have reported a TL priming advantage; that is, that jugde is a better prime for JUDGE than junpe is. (Note that this difference could not be because of the orthographic overlap of the matching letters [i.e., ju - - e], because both jugde and junpe contain those letters in their correct positions.)

The alternative view that has emerged is that there is considerable flexibility in coding letter position as embodied in a number of newer models of orthographic coding/word recognition (Davis, 2010; Gómez, Ratcliff, & Perea, 2008; Norris, 2006; Whitney, 2001). This alternative approach can be thought of as one involving more "relative-position-based" coding schemes. Examples are the Open-Bigram Models (Grainger & Van Heuven, 2003; Whit-

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ney, 2001), the Spatial-Coding Model (Davis, 1999, 2010), and the Overlap Model (Gómez et al., 2008). In Open-Bigram Models (Grainger & Van Heuven, 2003; Whitney, 2001), the basic assumption is that letter recognition involves detectors for sets of bigrams, both adjacent and nonadjacent bigrams. For example, the word JUDGE would activate bigram nodes for JU, UD, DG, GE, as well as JD, DE, UG. Reversed bigrams, such as DU would not be activated according to most versions of this type of model. This approach can explain TL priming effects, because TL primes share more bigrams with their target words than do SL primes.

An alternative explanation is provided by the Spatial-Coding Model. Davis (1999, 2010) proposed a spatial-coding scheme in which letter position is coded by the relative activation of position-independent letter nodes. The initial letter has the lowest position code, while the final letter has the highest position code, with the set of letters forming a spatial pattern that represents the relative activation of letters in the different positions. The spatial codes for TL primes and their base words will be more similar than those of SL primes and those same base words because the codes of the TL primes and their base words contain the same letters and, therefore, the same letter units are being activated during processing.

TL priming effects can also be explained by the Overlap Model (Gómez et al., 2008). The Overlap Model assumes that the coded letter positions for each letter can be considered to be normally distributed over the different positions, with the mean of the distribution being the letter's actual position. That is, in the word "judge," the letter "d" will be activated to the largest degree in Position 3, and to a lesser degree in Positions 2 and 4 and even, to some degree, in Positions 1 and 5 (Gómez et al., 2008). The existence of the "g" and the "d" in the TL nonword prime jugde, therefore, provides some evidence that letter string being read is, indeed, JUDGE, evidence not provided by the SL nonword prime jupte.

Other models that can also explain TL priming effects include the Bayesian Reader Model (Norris & Kinoshita, 2012) and the Time and Retinotopic Space (LTRS) Model (Adelman, 2011). What the previous models generally do not concern themselves with, however, is the question of the influence of visuospatial coordinates on the nature of orthographic coding. One hypothesis concerning the effects of visuospatial coordinates on word recognition was proposed by Grainger and Holcomb (2009), who argued that letter detectors are based on their relative location with respect to eye fixation on the horizontal meridian. Letters in words that are not presented horizontally require a transformation of the retinotopic coordinates into a special coordinate system to allow the activation of open bigrams. This special coordinate system for analyzing nonhorizontal words develops through exposure experience and is affected by the characteristics of the language being read. This type of account is essentially a perceptual learning account.

Dehaene et al. (2005) also posit that perceptual learning mechanisms are involved in how the orthographic code is created because they propose that there are dedicated neurons that only represent frequent, informative letters and bigrams. For instance, people may have detectors for CH, which often appears in English words, but not for CZ, which rarely appears in English words. This proposal is supported by the finding that early retinotopic areas produce more activation in response to letters than to rotated versions of letters (Chang et al., 2015). These types of hypotheses suggest that form priming effects (e.g., the TL priming effect) would be altered by changing the text's orientation.

In contrast, Witzel et al. (2011) argued that the mechanism responsible for form priming effects acts at a totally abstract level, a level at which visuospatial orientation no longer influences word processing. The letter positions are transformed from a spatial representation (either horizontal or vertical) into an abstract ordinal representation (first-to-last), which becomes the orthographic code. According to this hypothesis, people would show form priming effects regardless of the presented text's orientation, because the input letters would be rapidly transformed into this first-to-last code, and that code would then be used to access the lexicon regardless of the visuospatial orientation of the original stimulus.

To determine which type of hypothesis provides a better explanation of the nature of the orthographic code, Witzel et al. (2011) examined TL (and transposed character–TC) priming effects for Japanese-English bilinguals and English monolinguals by using a masked priming paradigm. These two groups seemed to provide a fruitful contrast because Japanese readers are used to reading both horizontally presented and vertically presented text, whereas English readers are not. The question was whether the two groups showed TL/TC priming effects when the stimuli were presented in both horizontal and vertical orientations. As expected, Japanese readers showed TL/TC priming effects in both horizontal and vertical presentation conditions. More centrally, native English speakers also showed TL priming effects when the text was presented in the vertical orientation (even though they lacked experience with vertical text), providing support for abstract letter unit accounts.

Perea, Marcet, and Fernández-López (2018) extended this investigation using Spanish words by comparing the magnitude of form priming effects in two different vertical orientations, marquee and 90° rotated orientations. Those authors found significant and equivalent masked form priming effects for primes and targets presented in the two orientations. These results are also potentially inconsistent with perceptual learning accounts but are quite consistent with approaches that treat letter/character codes as abstract representations (i.e., not tied to retinal positions).

In contrasting these two types of accounts, what is relevant to note, however, is that perceptual learning accounts do not directly predict null priming when a letter string is presented in a unique orientation. Even if the stimulus is rotated, causing the mental representation to be rotated, processing of the stimulus will continue and will normally be successful. What is the key prediction of these types of accounts is that there will be larger priming effects for canonically (i.e., horizontally) presented letter strings than letter strings presented in other orientations because noncanonical strings cannot take advantage of structures such as the neurons that are assumed to be dedicated to processing familiar letter pairs. Note also that these types of accounts make an additional prediction; that is, that transposition effects will be larger for horizontally presented letter strings (i.e., stimuli able to take advantage of such neurons) than other types of horizontally presented stimulus strings; for example, strings of symbols such as &%$#@, a prediction that has been supported in the literature (e.g., Duñabeitia, Dimitropoulou, Grainger, Hernández, & Carreiras, 2012; Massol, Duñabeitia, Carreiras, & Grainger, 2013). Note further that the specific comparison between horizontally presented words and nonhorizontally presented words was not evaluated either by Perea, Marcet, et al. (2018) or by Witzel et al. (2011) for their English readers.

The Present Research

Witzel et al.'s (2011) Japanese words were written in Katakana script. Although Katakana script is syllabic rather than alphabetic, it is much closer to alphabetic script than logographic scripts like Chinese. Each Katakana character represents a syllable or a combination of syllables (i.e., a *mora*), and, hence, represents a phonological unit. In contrast, Chinese characters have more complex internal structures, which are made up of between 1 and 36 strokes that are usually arranged into subcharacter "radicals," with those radical units being related directly to semantic and phonological information (Taft, Zhu, & Peng, 1999). Nonetheless, Chinese readers do show TC and other types of form priming effects (Gu & Li, 2015; Gu, Li, & Liversedge, 2015; Taft et al., 1999; Yang, 2013). Therefore, Chinese allows an opportunity to determine whether the results Witzel et al. and Perea, Marcet, et al. (2018) reported for alphabetic and syllabic languages can be extended to logographic languages. Because Perea et al. reported no difference between marquee and rotated words, we chose to use the marquee format for our vertical presentations in order to maintain consistency with Witzel et al.

What is worth noting at this point, however, is that most characters in Chinese are both syllables and morphemes (Zhou, Marslen-Wilson, Taft, & Shu, 1999). Thus, the possibility exists that what would appear to be form priming effects in Chinese may not be purely orthographic but may also be because of overlap at the morphemic and/or syllabic levels. That is, even if Chinese characters are transposed, they are, typically, able to provide appropriate morphemic and syllabic information even though that information would appear in incorrect positions. For example, 突如其来(/tū rú qí lái/, suddenly) is a Chinese four-character word that, when the middle characters are transposed 突其如来(/tū qí rú lái/), produces a character string that still contains the morphemes and syllables contained in the target word. If the reading system does have some tolerance for transpositions of morphemes and/or syllables, those dimensions could be partially contributing to any TC priming effects that one might observe in Chinese. We will return to this issue in the General Discussion.

The fact that the existence of TC priming effects has been established in Chinese is important because TC priming effects are not universal. Velan and Frost (2009), for example, found that Hebrew TC primes did not facilitate target word processing but, in fact, produced an inhibitory effect when the transposition of adjacent characters formed a legal root morpheme. This result has been taken to mean that the lexical space in Hebrew is encoded according to morphological root families, rather than according to orthographic structure, which may also be true of Chinese. Indeed, Grainger and Holcomb (2009) have argued that the special coordinate system is likely to be influenced by the characteristics of the language being investigated. It is, therefore, important that form priming effects and, in particular, TC priming effects, have been observed in Chinese because those types of results make the question of whether the effects vary as a function of orientation a viable one to investigate.

In the present research, therefore, we used Chinese words in an effort to explore form priming effects in logographic languages as a function of visuospatial orientation. What's also important to note is that Chinese readers, like Witzel et al.'s (2011) Japanese readers, do have some experience reading words in different orientations. Specifically, Chinese readers are familiar with left-to-right horizontal and top-to-bottom vertical text and, as well, they do have some (very limited) experience with right-to-left horizontal text while totally lacking experience with bottom-to-top text.

Experiment 1 involved a masked priming paradigm examining TC and repetition priming effects for native Chinese readers using text presented in both standard horizontal and vertical orientations. Based on the results from Witzel et al. (2011), we expected to find significant priming effects in both orientations. In Experiment 2, we used the masked priming paradigm to test whether Chinese readers would show a priming effect when the stimuli were presented in a right-to-left horizontal orientation. According to a perceptual learning account, although Chinese readers might show priming when the text is presented in a vertical orientation, there should be substantially less evidence of priming effects when the text is presented in this rather unfamiliar right-to-left orientation. In contrast, according to abstract letter/character unit accounts, there is no obvious reason that priming effects would not be found in any orientation in which reading can proceed somewhat normally (e.g., the right-to-left horizontal orientation). To jump ahead, priming was found with right-to-left text in Experiment 2 and, in Experiment 3, we examined whether those effects might disappear when the target and prime were not presented in the same orientation. Specifically, in Experiment 3 the primes were presented in a right-to-left horizontal orientation with the targets being presented in a standard left-to-right horizontal orientation. Finally, in Experiment 4, primes and targets were presented in a bottom-to-top vertical orientation (which is not one that exists in Chinese culture). According to any perceptual learning account, there is no possibility that priming effects due to the existence of dedicated neurons would emerge, while abstract letter/character unit accounts would not be inconsistent with any priming effects that might arise.

Experiment 1

Method

Participants. Forty native Chinese speakers who had normal or corrected-to-normal vision participated in this experiment. All indicated that they were highly proficiency in reading Simplified Chinese. They were all undergraduate students at Hunan University of Science and Technology (Xiangtan, Hunan, China). Twenty participants received the horizontal text condition first, and 20 participants received the vertical text condition first. All participants were given a small gift for their participation.

Materials. The stimuli for Experiment 1 were four-character simplified Chinese words. One hundred ninety-two low frequency words were chosen to serve as target words and another 192 low frequency words were chosen to serve as unrelated word primes. All of those words were selected from the *SUBTLEX-CH* database (Cai & Brysbaert, 2010). For the target words, their mean word frequency (per million) was 4.37 (range = 1.25–51.63). For the unrelated word primes, their mean word frequency (per million) was 4.41 (range = 1.22–37.83). All of the frequency values were obtained from the *SUBTLEX-CH* database (Cai & Brysbaert, 2010). There is no significant different in frequency between the target words and the unrelated word primes, $t(382) = -0.07$, $p = .947$.

In the repetition condition, the related prime was the target itself, and the control prime was the unrelated word prime selected for that target (e.g., 有所不同(ABCD)-有所不同(ABCD) versus 总的来说(EFGH)-有所不同(ABCD)). The primes and targets used different font styles and sizes (35-point Arial font for primes and 40-point Song font for targets). In the TC condition, the related primes were character strings in which the two middle characters in the target were transposed, whereas in the control condition for the TC condition (the SC condition), the two middle characters were substituted with two new characters (e.g., 有不所同[ACBD]-有所不同[ABCD] versus 有扑走同[AJKD]-有所不同[ABCD]). The target words were divided into two sets, and their use in the horizontal versus vertical orientation conditions was counterbalanced. In addition, there were four counterbalanced lists in each orientation condition, with 24 stimuli in each condition. We also created 384 orthographically legal nonwords (half to serve as target nonwords, the other half to serve as unrelated nonword primes for the nonword targets). These nonword stimuli were derived from the nonwords found in the Chinese Lexicon Project (Tse et al., 2017). The primes for the nonword targets were created in a similar fashion as the primes for the word targets (1/4 were repetition nonword primes, 1/4 were unrelated nonword primes, 1/4 were TC nonword primes and 1/4 were SC nonword primes), except that there was only one list of primes and targets.[1] For the word stimuli, the primes and their associated targets are listed in the Appendix.

Procedure. The participants were seated in a quiet room for testing. Eprime 2.0 software was used for data collection (Psychology Software Tools, Pittsburgh, PA; see Schneider, Eschman, & Zuccolotto, 2002). Each trial began with a mask (which consisted of eight hash marks ########) presented for 500 ms, followed by a prime for 50 ms, and then the target which was presented for 3,000 ms or until the participant responded. All the stimuli were presented in the center of the screen. Text presentation orientation (horizontal vs. vertical) was constant within a block and the order of the blocks was counterbalanced over participants (see Figure 1 for examples of a word presented in the various text orientations used in these experiments). Before the start of each block, participants performed 16 practice trials involving the stimulus orientation to be used in that block. Participants were asked to decide whether each presented (target) character string is a meaningful real word or a meaningless nonword. They were asked to press the "J" button if the presented target is a word and the "F" button if it is a nonword as quickly and as accurately as possible. This research was approved by the Western University REB (Protocol # 108835).

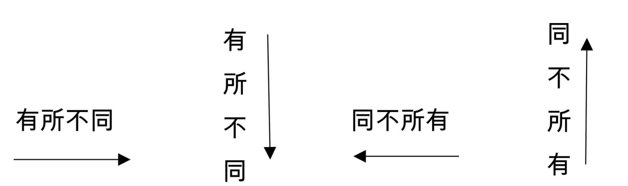

Figure 1. Examples of Chinese text presented in different text orientations.

Results

Latencies for incorrect responses were excluded from the latency analyses, as were latencies that were shorter than 300 ms (3.9% of the data). The latencies from the correct trials and the error rates were analyzed using generalized linear mixed-effects modeling in R Version 3.4.3 (R Development Core Team, 2015), treating subjects and items as random effects and treating orientation (horizontal vs. vertical), prime type (repetition vs. transposition), and priming (related vs. control) as fixed effects (Baayen, 2008; Baayen, Davidson, & Bates, 2008). Post hoc analyses were conducted by using the lsmeans package, Version 2.27–61 (Lenth, 2016), with Tukey's Honestly Significant Difference (HSD) adjustment for multiple comparisons. Prior to running the model, R-default treatment contrasts were changed to sum-to-zero contrasts (i.e., contr.sum) to help interpret lower-order effects in the presence of higher-order interactions (Levy, 2014; Singmann & Kellen, 2018). The model was fit by maximum likelihood with the Laplace approximation technique. The lme4 package, Version 1.1–15 (Bates, Mächler, Bolker, & Walker, 2015), was used to run the generalized linear mixed-effects model and obtain probability values.

A generalized linear mixed-effects model was used in the latency analyses in all the present experiments instead of a linear mixed-effects model because generalized linear models, unlike linear models, do not assume a normally distributed dependent variable and can, therefore, better accommodate the typically positively skewed distribution of reaction time (RT) data (Balota, Aschenbrenner, & Yap, 2013; Lo & Andrews, 2015).[2] A Gamma distribution was used to fit the raw RTs, with an identity link between fixed effects and the dependent variable (Lo & Andrews, 2015). Note that convergence tests for generalized linear mixed-effects models in the current version of lme4 tend to generate

[1] For the interested reader, we report the analyses of our nonword data for all of these experiments. However, because there was only one list of nonword primes and targets in each experiment (i.e., nonword targets were not counterbalanced over conditions), the nonword results should be interpreted very cautiously.

[2] Following a suggestion of one of the reviewers, we elected to use the generalized linear mixed-effects model and analyze raw RTs rather than following the more common practice of using linear mixed-effects models and normalizing raw RTs with a reciprocal transformation. The main reason for doing so was because nonlinear transformations systematically alter the pattern and size of interaction terms, casting doubt on the reliability of analyses of interactions. We did, however, replicate the analyses reported in the present article using linear mixed-effect models with inverse-transformed RTs (invRT = 1,000/RT) as the dependent variable. Those analyses replicated the pattern found with generalized linear mixed-effects models, with two exceptions, one of which is potentially notable, the interaction between Priming and Orientation in Experiment 1. To preview, the priming effect was 12 ms larger for the horizontal versus the vertical orientation words in Experiment 1. While this difference led to a significant interaction between Priming and Orientation in the linear mixed-effects model with transformed RTs, $\beta = -0.014$, $SE = 0.004$, $t = -3.874$, $p < .001$, it did not in the generalized linear mixed-effects model with raw RTs. Traditional mean-based ANOVAs also failed to return a significant Priming × Orientation interaction in both the subject, $F(1,39) = 3.10$, $p = .086$, and item, $F(1,191) = 2.39$, $p = .124$, analyses, suggesting that the inverse transformation of RTs in the linear mixed-effects model might have artificially exaggerated the difference in priming across orientations. The second exception is the 16-ms difference between the classic TC prime condition and the repetition prime condition in Experiment 3. That contrast was not a central one in that experiment.

many false positives (Bolker, 2018).[3] The statistical model for the latency analysis was: RT = glmer (RT ~ orientation * primetype * priming + (1|subject) + (1|item), family = Gamma(link = "identity")). The statistical model for the error rate analysis was: Accuracy = glmer (accuracy ~ orientation * primetype * priming + (1|subject) + (1|item), family = "binomial"). The mean RTs (in milliseconds) and percentage error rates for both the horizontal and vertical orientations are shown in Table 1 for the word targets.

Word trial latencies. The default model failed to converge even when fitting was restarted from the apparent optimum. We then proceeded to rerun the model using all available optimizers. Because all optimizers returned very similar values, we concluded that convergence warnings were false positives (see lme4 convergence help page). We report results only from the BOBYQA optimizer, which managed to converge.

There was no significant main effect of prime type, $\beta = -1.562$, $SE = 1.516$, $z = -1.03$, $p = .303$; however, a significant main effect of priming was observed, $\beta = -29.757$, $SE = 1.474$, $z = -20.19$, $p < .001$. Responses following related primes were significantly faster (608 ms) than were responses following control primes (669 ms). The main effect of orientation was also significant, $\beta = -33.828$, $SE = 1.457$, $z = -23.21$, $p < .001$, because latencies were longer with vertical text (677 ms) than with horizontal text (599 ms). The interaction between Priming and Prime Type was significant, $\beta = -7.573$, $SE = 1.467$, $z = -5.16$, $p < .001$, with the repetition priming effect being significantly larger than the TC priming effect. In the repetition priming condition, latencies following repetition primes (599 ms) were significantly faster than latencies following unrelated primes (674 ms), $\beta = -37.330$ $SE = 2.081$, $z = -17.941$, $p < .001$. When considering the TC priming effect, the SC primes (663 ms) led to significant slower latencies than did the TC primes (617 ms), $\beta = -22.184$, $SE = 2.078$, $z = -10.675$, $p < .001$. No other effects reached significance (all $ps > .10$).

Word trial accuracy. The main effect of prime type was significant, indicating an advantage for the repetition conditions (3.4%) over the TC conditions (4.2%), $\beta = 0.132$, $SE = 0.064$, $z = 2.055$, $p = .040$. In addition, there was a priming effect with the related primes (2.9%) leading to fewer errors than the unrelated primes (4.7%), $\beta = 0.280$, $SE = 0.065$, $z = 4.326$, $p < .001$. Neither the main effect of orientation nor any interaction was significant (all $ps > .10$).

Nonword trial latencies. The default model converged after restarting it from the apparent optimum. The only significant effect was that of orientation, $\beta = -46.605$, $SE = 1.864$, $z = -25.01$, $p < .001$, with faster responses to horizontally presented nonwords (719 ms) than to vertically presented nonwords (820 ms). No other main effect or interactions reached significance (all $ps > .10$).

Nonword trial accuracy. The main effect of priming was significant, with a small but significant reverse priming effect, $\beta = -0.207$, $SE = 0.082$, $z = -2.516$, $p = .012$. Control primes produced a slightly smaller error rate (2.8%) than did related primes (4.2%), The only significant interaction was Priming × Orientation, $\beta = -0.181$, $SE = 0.063$, $z = -2.892$, $p = .004$, indicating that the significant reverse effect of priming arose in the horizontal orientation condition ($\beta = -0.388$, $SE = 0.103$, $z = -3.785$, $p = .003$), but not in the vertical orientation condition ($\beta = -0.026$, $SE = 0.104$, $z = -0.253$, $p = .960$). There were no other main effects or interactions (all $ps > .05$).

Table 1
Mean Lexical Decision Latencies (Reaction Times [RTs], in Milliseconds) and Percentage Error Rate for Words in Experiment 1

	Repetition		TC	
Variable	RT	%E	RT	%E
Horizontal				
Related	557	2.5	575	3.3
Control	637	3.8	628	5.8
Priming	80***	1.3***	53***	2.5***
Vertical				
Related	640	2.4	660	3.3
Control	711	4.9	698	4.5
Priming	71***	2.5***	38***	1.2***

Note. TC = transposed character; %E = percentage error rate. The control primes for repetition primes were unrelated primes and for TC primes the control primes were substitution primes. The overall mean RT and error rate of the nonword targets in horizontal orientation were 719 ms and 3.8% respectively; The overall mean RT and error rate of the nonword targets in vertical orientation were 820 ms and 3.3% respectively.
*** $p < .001$.

Discussion

The results of Experiment 1 were quite similar to those of Witzel et al. (2011): Chinese native readers showed significant repetition and TC priming effects when stimuli were presented in both horizontal and vertical orientations. Unlike Japanese readers, however, Chinese readers were faster (78 ms) when processing horizontal text than vertical text, as well as showing a small, although nonsignificant, overall priming advantage (12 ms) with horizontal text. This pattern is consistent with the idea that Chinese readers may have had somewhat more experience in reading horizontal text than vertical text and, therefore, may have a reading system that is better tuned for processing horizontal text. The main point to be taken from Experiment 1, however, is that the finding that both repetition and TC priming effects were obtained in both text orientations, orientations that are familiar to Chinese readers, is consistent with both abstract letter/character unit accounts and perceptual learning accounts. The way to distinguish between accounts, therefore, is to examine the nature of priming effects for Chinese readers when processing text presented in a rarely experienced orientation, for example, a right-to-left horizontal orientation.

As noted, it is not the case that Chinese words are never written in the right-to-left horizontal orientation. Text of this nature occurs on signs at some temples and in the top scroll in a couplet.

[3] In all analyses, when convergence warnings were returned, the troubleshooting process followed the recommendations made by the lme4 authors (see the convergence help page in R), including restarting the fit from the apparent optimum position and rerunning the model with all available optimizers. The R syntax used to restart the model from the previous fit and rerun the model with all available optimizers is the following:

```
model.restart <- update(model, start = getME[model, c("theta", "fixef")])
source(system.file["utils", "allFit.R", package = "lme4"])
model.all < - allFit(model)
```

However, the right-to-left horizontal orientation is rarely experienced in modern Chinese culture. Therefore, a perceptual learning account would predict that Chinese readers should show little evidence of repetition or TC priming when reading text written in a right-to-left orientation, while effects of this sort would not be inconsistent with a generic abstract letter/character unit account. What should be noted at this point is that right-to-left primes do not appear to produce priming of either left-to-right or right-to-left targets in English (Davis, Kim, & Forster, 2008).

Experiment 2

Method

Participants. Forty-four Chinese native speakers who had normal or corrected-to-normal vision participated in this experiment. As in Experiment 1, all indicated that they were highly proficiency in reading Simplified Chinese. They were all graduate or undergraduate students either from Western University (London, Ontario, Canada) or Hunan University of Science and Technology (Xiangtan, Hunan, China). They were paid $5 for their participation or given a small gift. None had participated in Experiment 1.

Materials. Ninety-six of the target words (and their unrelated word primes) used in Experiment 1 were used in Experiment 2. The word frequency was matched between the target words and unrelated word primes. Twenty-four targets were primed by a repetition prime (e.g., 同不所有[DCBA]-同不所有[DCBA]), 24 by an unrelated word prime (e.g., 说来的总[HGFE[-同不所有[DCBA]), 24 by a TC prime (e.g., 同所不有[DBCA]-同不所有[DCBA]), and 24 by an SC prime (e.g., 同走扑有[DJKA]-同不所有[DCBA]). There were four counterbalanced lists for the word stimuli. Ninety-six of the target nonwords (and their unrelated nonword primes) used in Experiment 1 were used in Experiment 2. The primes for the nonword targets were created in a similar fashion as the primes for the word targets, except that there was only one list of primes and targets. All the other details were the same as in Experiment 1.

Procedure. The procedure was the same as in Experiment 1. The only difference was that all the stimuli, both primes and targets, were presented in the right-to-left horizontal orientation only. Before the start of the experiment, participants performed 16 practice trials with right-to-left oriented primes and targets.

Results

Latencies for incorrect responses were excluded, as were latencies that were shorter than 300 ms (3.9% of the data). Data were collapsed across study location (Canada vs. China) because of the fact that there was no three-way interaction between Orientation, Prime Type, and Priming. The statistical model for the latency data was: RT = glmer (RT ~ primetype * priming + (1|subject) + (1|item), family = Gamma(link = "identity"). In the error rate analysis, the statistical model was: Accuracy = glmer (accuracy ~ primetype * priming + (1|subject) + (1|item), family = "binomial"). The other details were same as in Experiment 1. The mean RTs (in milliseconds) and percentage error rates for this experiment are shown in Table 2 for the word targets.

Table 2
Mean Lexical Decision Latencies (Reaction Times [RTs], in Milliseconds) and Percentage Error Rate for Words in Experiment 2

	Repetition		TC	
Right-to-left horizontal	RT	%E	RT	%E
Related	810	3.4	815	3.3
Control	893	4.0	856	4.8
Priming	83***	.6	41***	1.5

Note. TC = transposed character; %E = percentage error rate. The control primes for repetition primes were unrelated primes and for TC primes the control primes were substitution primes. The overall mean RT and error rate of the nonword targets were 1068 ms and 5.6%, respectively.
*** $p < .001$.

Word trial latencies. There was a significant main effect of prime type, $\beta = 8.812$, $SE = 2.922$, $z = 3.02$, $p = .003$, and a significant main effect of priming, $\beta = -29.907$, $SE = 3.097$, $z = -9.66$, $p < .001$, because responses were faster overall in the TC conditions and for related primes. The interaction between Priming and Prime Type was also significant, $\beta = -8.342$, $SE = 3.058$, $z = -2.73$, $p = .006$, with the repetition priming effect (83 ms) being significantly larger than the TC priming effect (41 ms). In the post hoc analysis, there was a significant repetition priming effect, $\beta = -38.25$, $SE = 4.468$, $z = -8.561$, $p < .001$. In addition, in the TC condition, the TC primes led to significantly shorter latencies than the SC primes, $\beta = -21.565$, $SE = 4.234$, $z = -5.093$, $p < .001$.

Word trial accuracy. There was a marginal effect of priming ($\beta = 0.155$, $SE = 0.085$, $z = 1.814$, $p = .070$), indicating a tendency for targets following related primes to elicit fewer errors (3.4%) than targets following control primes (4.4%). Neither the main effect of prime type nor the interaction approached significance (all $ps > .10$).

Nonword trial latencies and accuracy. Neither of the main effects nor the interaction approached significance in either analysis (all $ps > .05$).

Discussion

The results of Experiment 2 essentially paralleled those of the horizontal and vertical orientation conditions in Experiment 1. That is, not only were both repetition and TC priming effects observed, the priming effect sizes were quite similar in size to those in Experiment 1. While being consistent with a generic abstract letter/character unit account, these results provide little support for a perceptual learning account of repetition and TC priming effects. Any perceptual learning accounts of these effects would predict that these effects would not arise or would be quite weak when the stimuli are presented in such an unfamiliar orientation.

An alternative explanation of the effects in Experiment 2, and one that would not necessarily be problematic for a perceptual learning account, is that those effects might have been an artifact of the demands of the task. Specifically, in line with a transfer-appropriate processing idea (e.g., Franks, Bilbrey, Lien, & McNamara, 2000; Kolers & Perkins, 1975; Kolers & Roediger, 1984), one could argue that, in order to deal with unfamiliar right-to-left targets, participants may have developed some sort of processing strategy for mentally reversing the order of the characters in the target, a strategy that was then also applied to prime processing. Experiment 3 was an attempt to examine this idea. The specific question was, will Chinese readers still show repetition and TC priming effects when the target is presented in the conventional left-to-right orientation following a right-to-left oriented prime (a result that, like the priming effects observed in Experiment 2, does not arise in English - Davis et al., 2008)?

Experiment 3

Method

Participants. Sixty Chinese native speakers who had normal or corrected-to-normal vision and who reported that they were highly proficient in reading Simplified Chinese participated in this experiment. They were all undergraduate students from Western University (London, Ontario, Canada) who participated for course credit in their introductory psychology course. None had participated in the previous experiments.

Materials. One hundred of the target words (and their unrelated word primes) used in Experiment 1 were used in Experiment 3. The word frequency was matched between the target words and unrelated word primes. Twenty targets were preceded by a (backward) repetition prime, that is, one that involves the same characters but presents them in a right-to-left orientation (e.g., 同不所有[DCBA]-有所不同[ABCD]), and 20 were preceded by an unrelated prime (i.e., a totally different word) that was also presented in the right-to-left orientation (e.g., 说来的总[HGFE]-有所不同[ABCD]). Three different prime types were used to investigate the TC priming effect. Twenty pairs involved what would be thought of as a (backward) classic TC prime; that is, one in which the prime is presented right-to-left but the middle two characters are transposed (e.g., 同所不有[DBCA]-有所不同[ABCD]). Note, however, that doing so creates a prime in which the middle two characters are in the same position in the prime and target and, therefore, is technically a prime involving a transposition of the first and fourth characters. Twenty pairs involved what could be thought of as a (backward) classic SC prime, that is one in which the prime was presented in a right-to-left orientation and the middle two characters are substituted (e.g., 同走扑有[DJKA]-有所不同[ABCD]). Finally, 20 primes were used that may be a better control for evaluating TC priming. These primes, external substitution primes, maintain the middle two characters of the prime in their appropriate positions (as in the classic TC primes discussed above) but replace the first and fourth characters of the target (e.g., 走所不扑[JBCK]-有所不同[ABCD]).

There were five counterbalanced lists for the word stimuli. One hundred of the target nonwords (and their unrelated nonword primes) used in Experiment 1 were used in Experiment 3. Just as in the word conditions, these nonword targets were preceded by five different types of primes and, as in the previous experiments, there was only one list of nonword primes and targets. The other details were the same as in Experiment 1.

Procedure. The procedure was the same as in Experiment 1, the only difference being that all the primes were presented in the right-to-left horizontal orientation, while all the targets were presented in the normal (left-to-right) horizontal orientation. Before the start of the experiment, participants performed 20 practice trials involving right-to-left oriented primes and left-to-right oriented targets.

Results

Latencies for incorrect responses were excluded, as were latencies that were shorter than 300 ms (3.0% of the data). Unlike Experiment 1 and Experiment 2, the design of Experiment 3 involved a single fixed effect, Prime Type, with five levels (repetition, unrelated, classic TC, classic SC, external SC). The function analysis of variance (ANOVA) in the car package Version 2.1–2 (Fox & Weisberg, 2016) was used to test the significance of the Prime Type factor. The statistical model for the latency data was: RT = glmer (RT ~ primetype + (1|subject) + (1|item), family = Gamma(link = "identity")). In the error rate analysis, the model was: Accuracy = glmer (accuracy ~ primetype + (1|subject) + (1|item), family = "binomial"). The other details were the same as in Experiment 1. The mean RTs (in milliseconds) and percentage error rates for Experiment 3 are shown in Table 3 for the word targets.

Word trial latencies. The default model converged after restarting it from the apparent optimum. There was a main effect of prime type, $\chi^2 = 185.98$, $p < .001$. In the post hoc analysis, participants showed a significant repetition priming effect (52 ms), $\beta = -53.607$, $SE = 6.715$, $z = -7.984$, $p < .001$. Significant TC priming was observed when comparing the classic TC prime condition with both the external SC prime condition (51 ms), $\beta = 48.013$, $SE = 5.252$, $z = 9.141$, $p < .001$, and the classic SC prime condition (56 ms), $\beta = 54.252$, $SE = 5.507$, $z = 9.852$, $p < .001$. The classic SC prime condition did not differ from the external SC prime condition, $\beta = -6.239$, $SE = 5.300$, $z = -1.177$, $p = .765$. Note that the classic TC prime condition produced latencies that were numerically, but not significantly, shorter than those in the repetition prime condition, $\beta = 13.555$, $SE = 5.832$, $z = 2.324$, $p = .137$. Finally, the mean latency in the unrelated prime condition was longer than the mean latency in the external SC prime condition, $\beta = -19.149$, $SE = 5.980$, $z = -3.202$, $p = .012$, but did not differ from the mean latency in the classic SC prime condition, $\beta = -12.911$, $SE = 6.148$, $z = -2.100$, $p = .220$.

Word trial accuracy. The main effect of prime type was significant, $\chi^2 = 10.224$, $p = .037$. In the post hoc analysis, participants showed a significant repetition priming effect (1.9%), $\beta = 0.817$, $SE = 0.279$, $z = 2.929$, $p = .028$. Repetition primes

Table 3
Mean Lexical Decision Latencies (Reaction Times [RTs], in Milliseconds) and Percentage Error Rate for Words in Experiment 3

Condition	RT	%E
Repetition prime	664	1.8
Unrelated prime	716	3.7
Classic transposed prime	648	2.7
Classic substitution prime	704	3.5
External substitution prime	699	3.1

Note. The overall mean RT and error rate of the nonword targets were 881 ms and 3.6%, respectively.

(1.8%) also elicited less errors than classic SC primes (3.5%), although only marginally so, $\beta = -0.762$, $SE = 0.281$, $z = -2.710$, $p = .052$.

Nonword trial latencies. The default model converged after restarting it from the apparent optimum. There was a main effect of prime type, $\chi^2 = 11.86$, $p = .018$. The post hoc analysis revealed that, compared with repetition primes (899 ms), external SC primes (877 ms) led to faster latencies, $\beta = -20.632$, $SE = 7.170$, $z = -2.877$, $p = .033$, and so did (although only marginally so) classic TC primes (875 ms), $\beta = -21.289$, $SE = 7.907$, $z = -2.692$, $p = .055$. No other contrasts reached significance (all ps $> .1$).

Nonword trial accuracy. The main effect of prime type was not significant, $\chi^2 = 6.01$, $p = .199$.

Discussion

To avoid inducing participants to adopt a processing strategy for dealing with unfamiliar right-to-left targets, one based on mentally reversing the order of the characters in the target which then would also be applied during prime processing, the targets in Experiment 3 were presented in the conventional left-to-right orientation. The most important result in this experiment was that there was a significant (backward) repetition priming effect. Repetition primes presented in the completely opposite (right-to-left) orientation primed targets presented in the standard left-to-right horizontal orientation.

Experiment 3 also provided evidence of a (backward) TC priming effect when measured against both of our control conditions. Because these patterns generally parallel those from Experiment 2, a reasonable conclusion would be that the results in Experiment 2 were not because of participants adopting a strategy involving a mental reversal of the order of the target's (and prime's) characters. Rather, they are more likely because of the abstract nature of representations in the orthographic code.

The main question of Experiment 3 concerned whether right-to-left primes produce priming for left-to-right targets in Chinese, just as they did for right-to-left targets in Experiment 2 (but not as what they appear to do in English; Davis et al., 2008). Whereas the answer is that they do produce priming, it may be worth noting that the size of the "repetition" effect in Experiment 3 (52 ms) was slightly smaller than the size of the parallel effect in Experiment 2 (83 ms). Part of that difference was likely because of the fact that responding was approximately 150 ms faster in Experiment 3, although that is probably not the only reason for the difference in the effect sizes. Rather, right-to-left primes are probably at least a bit more orthographically similar to the right-to-left targets used in Experiment 2 than to the left-to-right targets used in Experiment 3.

What is also potentially relevant is that, in contrast to the results in Experiment 2, the "repetition" priming effect and what we take to be the TC priming effect were equivalent in size in Experiment 3. In an attempt to gain a bit more of an understanding of the principles involved here, it may be of some value to examine the impact of transposing characters in Experiment 3 a bit more closely.

Essentially, right-to-left oriented primes with their middle two characters then transposed (what we are calling classic TC primes, e.g., DBCA) led to faster latencies than both what we are calling classic SC primes (e.g., (DJKA) and primes involving the same middle characters in the same positions as in the target but having different exterior characters, external substitution primes (JBCK). As noted, these TC priming effects are a bit hard to characterize because all three of these prime types can be interpreted in more than one way. As a result, it's not at all clear which of these two latter prime types would be the most appropriate control condition in this situation (or, if neither of these is appropriate, what the appropriate condition would be). That is, the DBCA-DJKA contrast could be characterized as representing the value of having correct characters in the two middle positions rather than representing the impact of a right-to-left written TC prime. Similarly, the DBCA-JBCK contrast could be characterized as representing the impact of transposing the first and fourth characters in a left-to-right prime.

When thought about in those ways, however, one seems to arrive at an illogical conclusion. This second contrast (DBCA-JBCK) produced a 51 ms priming effect (699–648), which when thought about as representing the impact of a left-to-right oriented prime, implies that transposing the exterior two characters (rather than replacing them) was quite impactful. In contrast, the difference between the classic SC prime condition and the completely unrelated condition (DJKA-HGFE) was a nonsignificant 12 ms (704–716) suggesting that the impact of transposing the two exterior characters is minimal at best. Needless to say, it's hard to reconcile these two conclusions. Therefore, in the present situation (i.e., in Chinese), the more reasonable conclusion is that there is something crucial about the prime and target sharing all their characters even if those characters are not in the same positions in the prime and target (i.e., the (backward) classic TC prime, DBCA, or the (backward) repetition prime, DCBA, work well whereas primes containing 2 of the 4 target characters, JBCK and DJKA, do not).

In Experiment 4, we sought to push the contrast between perceptual learning and abstract letter/character unit accounts one step further by presenting the primes and targets in a completely unfamiliar bottom-to-top orientation. According to any perceptual learning account, there should be very little evidence of priming effects from these prime-target pairs, whereas a generic abstract letter/character unit account would seem to have the ability to explain such an effect.

Experiment 4

Method

Participants. Thirty-four Chinese native speakers who had normal or corrected-to-normal vision and who reported that they were highly proficient in reading Simplified Chinese participated in this experiment. They were all undergraduate students from Western University (London, Ontario, Canada) who participated for course credit in their introductory psychology course. Fourteen of these participants had participated in Experiment 3.

Materials. Ninety-six of the target words (and their unrelated word primes) used in Experiment 1 were used in Experiment 4. The word frequency was matched between the target words and the unrelated word primes. Unlike in Experiment 1, only TC priming was investigated with 48 targets being primed by a TC prime (e.g., 有不所同[ACBD]-有所不同[ABCD]) and 48 by an SC prime (e.g., 有扑走同[AJKD]-有所不同[ABCD]). There were two counterbalanced lists for word stimuli. Ninety-six of the target nonwords (and their unrelated nonword primes) used in Experiment 1 were used in Experiment 4. As with the word targets, the nonword targets were preceded either by a TC prime or an SC prime and, as in previous experiments, only one list of nonword primes and targets was used. The other details were the same as in Experiment 1.

Procedure. The procedure was the same as in Experiment 1 with the only difference being that all the stimuli (primes and targets) were presented in the bottom-to-top orientation. Before the start of the experiment, participants performed eight practice trials.

Results

Latencies for incorrect responses were excluded, as were latencies that were shorter than 300 ms (3.8% of the data). The design of this experiment involved a single fixed effect, Prime Type, with two levels (TC vs. SC). The final statistical model for the latency data was: RT = glmer (RT ~ primetype + (1|subject) + (1|item), family = Gamma(link = "identity")). In the error analysis, the final model was: Accuracy = glmer (accuracy ~ primetype + (1|subject) + (1|item), family = "binomial"). The other details were the same as in Experiment 1. The mean RTs (in milliseconds) and percentage error rates for Experiment 4 are shown in Table 4 for the word targets.

Word trial latencies and accuracy. The 50-ms difference between the TC prime (869 ms) and the SC prime (919 ms) conditions was significant, $\beta = 25.788$, $SE = 3.379$, $z = 7.63$, $p < .001$. The TC primes also led to significantly fewer errors (2.9%) than did the SC primes (4.5%), $\beta = -0.257$, $SE = 0.099$, $z = -2.583$, $p = 0.01$.

Nonword trial latencies and accuracy. In the latency data, there was a significant reverse main effect of prime type, with the SC primes (1108 ms) leading to faster latencies than the TC primes (1146 ms), $\beta = -18.148$, $SE = 6.362$, $z = -2.85$, $p = .004$. There was no significant main effect of prime type in the accuracy analysis ($p > .10$).

Discussion

Although the stimuli in Experiment 4 were presented in an entirely novel orientation, participants still produced a clear TC priming effect, which was essentially the same size as the TC priming effects in Experiment 1 and 2. This result once again provides support for the argument that these types of effects are much better able to be explained in terms of an abstract letter/character unit account rather than in terms of a perceptual learning account.

Table 4
Mean Lexical Decision Latencies (Reaction Times [RTs], in Milliseconds) and Percentage Error Rates for Words in Experiment 4

Condition	RT	%E
Transposed prime	869	2.9
Substitution prime	919	4.5
Priming	50***	1.6*

Note. The overall mean RT and error rate of the nonword targets were 1,127 ms and 3.6%, respectively.
* $p < .05$. *** $p < .001$.

General Discussion

Four masked priming experiments involving the presentation of stimuli in different orientations were carried out to investigate the role of text orientation in orthographic processing and to provide a basis for contrasting perceptual learning-based accounts of form priming in Chinese against accounts based on abstract letter/character units. The results of Experiment 1 were that repetition and TC priming effects were observed for stimuli presented in both horizontal and vertical orientations, paralleling Witzel et al.'s (2011) results. The only difference between experiments was that, unlike Witzel et al.'s Japanese readers whose performance was similar with horizontal and vertical words, our Chinese readers were considerably (72 ms) faster and their priming effects were slightly (12 ms), but not significantly, stronger with horizontal text than with vertical text, a pattern that would be consistent with either type of account. In Experiment 2, Chinese native readers showed masked repetition and TC priming effects when the text was presented in a right-to-left orientation. In Experiment 3, we still obtained strong repetition and, what we take as, TC priming effects when left-to-right targets followed right-to-left primes. Finally, even though we used an entirely new text orientation in Experiment 4, participants produced a TC priming effect that was virtually the same size as those in Experiments 1 and 2, providing probably the clearest evidence against a perceptual learning account of our form priming effects.

More specifically, taken together, our finding of priming in all situations investigated and essentially equivalent priming in the repetition conditions and in the TC conditions in Experiments 1, 2 and 4 are inconsistent with Grainger and Holcomb's (2009) special coordinate system account and Dehaene et al.'s (2005) LCD model. Rather, the processes which mediate our priming effects appear to occur at an abstract level of representation, in line with Witzel et al.'s (2011) abstract letter unit account. This account assumes that the orthographic code is created by transforming a visuospatial code into an ordinal code. Thus, regardless of the text orientation, what the reader takes as the beginning letter/character is assigned to the first position, and the next letter/character is assigned to the second position, and so on. Crucially, the presented text orientation is not directly related to this orthographic code, as readers appear to convert the visuospatial code into an abstract code quite rapidly and doing so may very well be required before lexical processing can advance.

Perhaps surprisingly, we were even able to expand this conclusion to the situation in which the prime, but not the target, was written right-to-left. What is also important to recognize is that these effects (and the TC priming effect with the bottom-to-top orientation) were demonstrated with Chinese four-character words. It's not inevitable that such effects would be found with other scripts in other languages. In fact, in English, Guerrera and Forster (2008) found that, although there was a reasonably large priming effect when eight-letter targets contained all the letters of the prime but with only two of those eight letters in the same position in the prime and target, they failed to detect a priming effect with more extreme transposition primes, such as when edisklaw and isedawkl primed the target SIDEWALK. That is, their data support the idea that there is a limit to the amount of distortion in the ordering of letters/characters that the reading system can tolerate.

At mentioned previously, there would appear to be one examination of the question of the system's ability to tolerate backward primes and targets in the English language literature. Davis et al. (2008) presented backward targets (e.g., ECAF), with each target preceded by either a forward prime (e.g., FACE) or a backward prime (e.g., ECAF). Although forward primes produced a facilitation effect, backward primes did not (in contrast to our results in Experiment 2), even though the targets were also presented in the backward direction. This result implies that there is a basic difference in the level of tolerance for position distortions in the orthographic code between Chinese and English readers, although it could also reflect a difference in how reverse spelling targets are processed in the two languages. The latencies, for example, in Davis et al. were approximately 200 ms longer than in the present Experiment 2 suggesting that Davis et al.'s subjects had considerably more difficulty dealing with right-to-left written words than our subjects did.[4]

The question is, therefore, whether the backward priming effects observed here can be successfully accommodated within any of the current abstract letter/character accounts. That is, can any of those models mentioned previously (e.g., Adelman, 2011; Davis, 2010; Gómez et al., 2008; Grainger & Van Heuven, 2003; Whitney, 2001) actually explain the large priming effects we observed from primes presented in noncanonical orientations (Experiments 2, 3, and 4)? At present, the answer would seem to be no. Most of those accounts do not currently have a mechanism for tolerating the level of distortion in terms of letter positions found in our primes and targets, which, of course, means that the null priming effect reported by Davis et al. (2008) is consistent with those models. Our results, in contrast, do raise problems for those models even though, in theory, they would all seem to have the ability to explain priming of this sort if the appropriate assumptions were made. Rather than expanding any of the models (by adding new assumptions) in an attempt to account for the present data, however, what seems to be a more fruitful direction to go would be to ask whether our results might have arisen at a level other than the orthographic level. For example, as noted previously, one could propose that the effects may be morphemic or syllabic/phonological effects if it's reasonable to assume that priming based on morphemic or syllabic/phonological relationships is capable of tolerating distortions in the ordering of that type of information.

More specifically, Chinese characters usually represent a single morpheme, and transposing morphemes will, most of the time, still maintain the morphemic relationship between the prime and target. There is a common consensus that processing morphologically complex words in English does require some type of morphemic processing (Crepaldi, Rastle, Coltheart, & Nickels, 2010; Crepaldi, Rastle, Davis, & Lupker, 2013; Drews & Zwitserlood, 1995; New, Brysbaert, Segui, Ferrand, & Rastle, 2004), and there is no reason to believe that similar conclusions would not apply to Chinese. Indeed, Zhang and Peng's (1992) Chinese word recognition model is based on the idea that there is a separate morpheme level involved in processing during word recognition. Supporting evidence for that conclusion includes Taft, Zhu, and Peng's (1999) demonstration that the latencies for transposable Chinese compound words (multiple morpheme words in which transposing the morphemes forms a different word) were longer in a lexical-decision task than for nontransposable compound words. Taft et al. interpreted their results as suggesting that Chinese characters have position free representations, that is, that position information is highly flexible when processing character level representations, a conclusion that would be compatible with the present results.

Additional support for this idea comes from Wu, Tsang, Wong, and Chen (2017) who showed that target words (e. g.,公園, city park) induced a similar P200 component when preceded by primes in which a shared character plays a similar morphemic role (e.g., 公眾, citizen) versus primes in which that shared character in the prime and target does not (e.g., 公雞, rooster). However, an N400 component was only produced when the targets were preceded by morphemically related primes. The difference between these two prime types could not be because of a difference in orthographic similarity because the two primes share the same character with the target (e.g., 公, city), nor is it likely to have been because of semantics, because semantic primes not sharing a morpheme (e.g., 草地, lawn) produced only very small effects in both the behavioral and ERP data. This study suggests that morpheme level processing in Chinese does occur during an early stage of visual word recognition, consistent with models like the hybrid model (Diependaele, Sandra, & Grainger, 2009) and the Lemma model (Taft & Nguyen-Hoan, 2010). In the latter model, lemmas are immediately and unconsciously encoded once the morpho-orthographic decomposition has finished, prior to the whole word processing stage. The implication for the present data is that the unusual orientation priming effects for four-character Chinese words observed here could possibly have been morphemic effects if the morphemic processing system can tolerate the level of character transposition involved in our experiments.

As an alternative, Chinese characters are also syllables and reversing their order changes only the order of the word's phonology. Some studies have indicated that phonological priming effects do arise in Chinese which has led some researchers to suggest that the syllable is a functional unit in spoken word production in Chinese (Schiller, 1999; You, Zhang, & Verdonschot, 2012). For example, in You et al.'s (2012) examination of syllable priming effects during Chinese spoken word production, their results indicated that when primed by CV (密,/mi4/, dense) primes, CV targets (迷你,/mi2.ni3/, mini)) were named faster than when they were primed by CVN (*N* represents word endings involving n/or/ng/, e.g., 敏,/min3/, agile), CVG (G represents word endings with glide sound, e.g., 卖,/mai3/, sale) or unrelated primes (耍,/shua3/, play). Qu, Damian, and Li (2016) also found syllable facilitation priming effects in a picture naming task, whereas Zhou and Marslen-Wilson (2009) found mixed pseudohomophones (e.g., 严革,/yan2ge2/), which retain one character in the same position as the target (e.g., 严格,/yan2ge2/, terrible) produced an inhibitory effect in comparison to control nonword primes. In contrast, however, Wong, Wu, and Chen (2014) showed no significant differ-

[4] Morris and Still (2012) also investigated backward prime priming effects in English. However, their experiment differs from Davis et al.'s (2008) and the current investigation in that their backward primes were themselves words (e.g., flow-WOLF) and that those primes produced an inhibitory, rather than a faciliatory, effect. One could certainly imagine that, as Morris and Still suggest, their inhibition effect is a lexical competition phenomenon and, hence, it's not clear to what extent Morris and Still's results would be relevant to the results reported here.

ence between a syllabic related prime condition and an unrelated prime condition (in either behavioral or ERP results), which caused them to argue that the role of phonology is limited during Chinese word recognition. Everything considered, it does appear that the answer to the question of whether the syllable is a functional unit in Chinese visual word processing is still not entirely clear and, therefore, whether (and how) shared syllables can produce inhibitory or faciliatory priming is yet to be determined. In general, however, what should be noted is that the previous studies do not rule out the possibility that our priming effects from primes in different orientations may have had somewhat of a syllabic basis.

In this context, it is worth noting that Witzel et al. (2011) used Japanese kana words as their experimental stimuli. Each kana character is essentially a syllable. Therefore, one could also propose that what Witzel et al. have shown is a transposed syllable/phonological priming effect rather than an orthographically based TC priming effect. Potentially arguing against that idea are two articles showing that transposed phoneme nonwords are not effective primes in Japanese. That is, Perea and Pérez (2009) failed to find any masked transposed phoneme priming effects (a.re.mi.ka-a.me.ri.ka vs. a.ma.ro.ka-a.me.ri.ka) with Japanese Kana words in two experiments. Furthermore, Perea, Nakatani, and van Leeuwen (2011) found similar fixation times for transposed-consonant nonwords (a.re.mi.ka [アレミカ]–a.ri.me.ka [アリメカ]) versus orthographic control nonwords (a.ke.hi.ka [アケヒカ]–a.me.ri.ka [アメリカ]) in the periphery in an event boundary paradigm. A counter argument, however, is that there is good evidence that the mora (essentially a syllable) rather than the phoneme is the basic phonological unit in Japanese (e.g., Ida, Nakayama, & Lupker, 2015). Therefore, it isn't clear what implications Perea and colleagues' lack of phoneme transposition effects would have for the character transposition effects reported by Witzel et al.

Nonetheless, as Grainger (2018) has argued, orthographic processing is the main interface between lower-level visual coding and higher-level linguistic processing in essentially all languages (Grainger, 2016; Grainger, Dufau, & Ziegler, 2016). Consistent with this idea, all of the models assuming a "relative-position-based" coding scheme also assume that letter identity and letter position coding occur during an early orthographic stage, with phonological processing occurring subsequently. As a result, no matter what the input language is, the implication is that orthographic processing should always dominate the visual word recognition process with morphemic and syllabic/phonological processing playing a secondary role. Hence, the default assumption would seem to be that the effects reported in the present article are orthographically based.

In summary, the present experiments showed significant repetition and TC priming effects in the text orientations investigated here (e.g., left-to-right horizontal, top-to-bottom, right-to-left horizontal and bottom-to-top orientations). These findings suggest that in a logographic script, the processes which mediate these form priming effects occur at an abstract level of representation, supporting Witzel et al.'s (2011) abstract letter unit account over any perceptual learning account. How models of orthographic coding can fully explain these results remains an issue for future model development. Before doing so, however, it would seem to be worthwhile to at least investigate the possibility that some of the priming effects observed here may not be orthographic but may be either morphemic or syllabic/phonological and, hence, would not need to be explained by models of orthographic coding.

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Appendix

Word Stimuli Used in the Experiments

	Condition				
Target	Repetition prime	TC prime	Classic SC prime	Unrelated prime	External SC prime
遮遮掩掩	遮遮掩掩	遮掩遮掩	遮救过掩	新奥尔良	救掩遮过
有所不同	有所不同	有不所同	有扑走同	总的来说	扑不所走
突如其来	突如其来	突其如来	突探古来	防毒面具	探其如古
完美无缺	完美无缺	完无美缺	完刹除缺	随时随地	刹无美除
了如指掌	了如指掌	了指如掌	了船标掌	引人注意	船指如标
出人意料	出人意料	出意人料	出违控料	时时刻刻	违意人控
微不足道	微不足道	微足不道	微对字道	深思熟虑	对足不字
有线电视	有线电视	有电线视	有眼泣视	每时每刻	眼电线泣
截然不同	截然不同	截不然同	截空款同	改头换面	空不然款
水深火热	水深火热	水火深热	水淡落热	独一无二	淡火深落
不值一提	不值一提	不一值提	不上仰提	精疲力竭	上一值仰
为时过早	为时过早	为过时早	为行义早	一举一动	行过时义
不省人事	不省人事	不人省事	不贯守事	种族主义	贯人省守
总而言之	总而言之	总言而之	总模品之	阿拉斯加	模言而品
精彩绝伦	精彩绝伦	精绝彩伦	精播秧伦	无时无刻	播绝彩秧
竭尽全力	竭尽全力	竭全尽力	竭违行力	指指点点	违全尽行
不切实际	不切实际	不实切际	不加小际	无足轻重	加实切小
第一夫人	第一夫人	第夫一人	第集力人	重归于好	集夫一力
自以为是	自以为是	自为以是	自信取是	别无选择	信为以取
情不自禁	情不自禁	情自不禁	情审规禁	福尔摩斯	审自不规
混为一谈	混为一谈	混一为谈	混矿化谈	天翻地覆	矿一为化
挺身而出	挺身而出	挺而身出	挺封制出	才华横溢	封而身制
电子游戏	电子游戏	电游子戏	电地态戏	事与愿违	地游子态
光明正大	光明正大	光正明大	光充用大	自言自语	充正明用
心不在焉	心不在焉	心在不焉	心逃陷焉	万无一失	逃在不陷

(*Appendix continues*)

Appendix (*continued*)

Target	Condition				External SC prime
	Repetition prime	TC prime	Classic SC prime	Unrelated prime	
乳臭未干	乳臭未干	乳未臭干	乳脚瘤干	可不可以	脚未臭瘤
不久以后	不久以后	不以久后	不送谢后	精力充沛	送以久谢
无论如何	无论如何	无如论何	无监取何	胡言乱语	监如论取
前功尽弃	前功尽弃	前尽功弃	前战族弃	莫名其妙	战尽功族
从未有过	从未有过	从有未过	从木舢过	小题大做	木有未舢
胡说八道	胡说八道	胡八说道	胡增退道	为时已晚	增八说退
走投无路	走投无路	走无投路	走纠见路	摇摆不定	纠无投见
下定决心	下定决心	下决定心	下解缘心	愤世嫉俗	解决定缘
不可理喻	不可理喻	不理可喻	不作兵喻	未成年人	作理可兵
显而易见	显而易见	显易而见	显挂出见	不速之客	挂易而出
刮目相看	刮目相看	刮相目看	刮现下看	进退两难	现相目下
刀枪不入	刀枪不入	刀不枪入	刀拼开入	一丁点儿	拼不枪开
无动于衷	无动于衷	无于动衷	无下定衷	大名鼎鼎	下于动定
身不由己	身不由己	身由不己	身闭室己	滔滔不绝	闭由不室
乱七八糟	乱七八糟	乱八七糟	乱法议糟	一天到晚	法八七议
分道扬镳	分道扬镳	分扬道镳	分满船镳	脱胎换骨	满扬道船
尽管如此	尽管如此	尽如管此	尽录出此	激动人心	录如管出
远走高飞	远走高飞	远高走飞	远安年飞	一动不动	安高走年
辩护律师	辩护律师	辩律护师	辩游区师	无缘无故	游律护区
忍无可忍	忍无可忍	忍可无忍	忍互决忍	实话实说	互可无决
无理取闹	无理取闹	无取理闹	无祭化闹	换句话说	祭取理化
无懈可击	无懈可击	无可懈击	无据除击	圣诞翻人	据可懈除
鸡尾酒会	鸡尾酒会	鸡酒尾会	鸡起缓会	哭哭啼啼	起酒尾缓
破门而入	破门而入	破而门入	破会礼入	焦头烂额	会而门礼
价值连城	价值连城	价连值城	价部领城	理所当然	部连值领
毫无用处	毫无用处	毫用无处	毫苦热处	遥遥领先	苦用无热
焕然一新	焕然一新	焕一然新	焕国士新	不为人知	国一然士
光彩照人	光彩照人	光照彩人	光人场人	格格不入	人照彩场
高速公路	高速公路	高公速路	高门岸路	除此之外	门公速岸
难以忘怀	难以忘怀	难忘以怀	难睡幕怀	偷偷摸摸	睡忘以幕
最高法院	最高法院	最法高院	最蛋碎院	说来话长	蛋法高碎
恐怖主义	恐怖主义	恐主怖义	恐椅窗义	全神贯注	椅主怖窗
袖手旁观	袖手旁观	袖旁手观	袖白棉观	长大成人	白旁手棉
并非如此	并非如此	并如非此	并献奏此	一劳永逸	献如非奏
多管闲事	多管闲事	多闲管事	多挂除事	此时此刻	挂闲管除
一塌糊涂	一塌糊涂	一糊塌涂	一高短涂	也就是说	高糊塌短
自掘坟墓	自掘坟墓	自坟掘墓	自放押墓	一无所知	放坟掘押
无所畏惧	无所畏惧	无畏所惧	无精略惧	西班牙语	精畏所略
心神不宁	心神不宁	心不神宁	心披下宁	墨西哥人	披不神下
光天化日	光天化日	光化天日	光阅件日	一声不吭	阅化天件
歇斯底里	歇斯底里	歇底斯里	歇补去里	成千上万	补底斯去
一路顺风	一路顺风	一顺路风	一协心风	鬼鬼祟祟	协顺路心
无所不能	无所不能	无不所能	无杀口能	合情合理	杀不所口
有史以来	有史以来	有以史来	有配数来	难以忍受	配以史数
无处不在	无处不在	无不处在	无惜重在	一网打尽	惜不处重
告一段落	告一段落	告段一落	告跨上落	毫不犹豫	跨段一上
好不容易	好不容易	好容不易	好偿赐易	筋疲力尽	偿容不赐
有鉴于此	有鉴于此	有于鉴此	有征者此	流言蜚语	征于鉴者
感激不尽	感激不尽	感不激尽	感微见尽	舒舒服服	微不激见
二氧化碳	二氧化碳	二化氧碳	二预位碳	甜言蜜语	预化氧位
难以启齿	难以启齿	难启以齿	难探起齿	千真万确	探启以起
千载难逢	千载难逢	千难载逢	千私诈逢	诺贝尔奖	私难载诈
束手无策	束手无策	束无手策	束知理策	心烦意乱	知无手理
白手起家	白手起家	白起手家	白官船家	恰到好处	官起手船
一无所获	一无所获	一所无获	一戴入获	无话可说	戴所无入
自作主张	自作主张	自主作张	自敬人张	不知所云	敬主作人
诸如此类	诸如此类	诸此如类	诸辞示类	成百上千	辞此如示
一如既往	一如既往	一既如往	一门债往	置身事外	门既如债
犹豫不决	犹豫不决	犹不豫决	犹战方决	全力以赴	战不豫方
毫无疑问	毫无疑问	毫疑无问	毫呈状问	鸡皮疙瘩	呈疑无状

(*Appendix continues*)

Appendix (*continued*)

Target	Condition				External SC prime
	Repetition prime	TC prime	Classic SC prime	Unrelated prime	
直升飞机	直升飞机	直飞升机	直祝望机	虚张声势	祝飞升望
绝大多数	绝大多数	绝多大数	绝空漏数	天衣无缝	空多大漏
开门见山	开门见山	开见门山	开籍著山	一模一样	籍见门著
大海捞针	大海捞针	大捞海针	大官政针	半途而废	官捞海政
于事无补	于事无补	于无事补	于练着补	蠢蠢欲动	练无事着
物理学家	物理学家	物学理家	物焦心家	大发雷霆	焦学理心
不合时宜	不合时宜	不时合宜	不幼期宜	夷为平地	幼时合期
视而不见	视而不见	视不而见	视融出见	所作所为	融不而出
拭目以待	拭目以待	拭以目待	拭收载待	一触即发	收以目载
见不得人	见不得人	见得不人	见画掉人	土生土长	画得不掉
中产阶级	中产阶级	中阶产级	中冲干级	司法部长	冲阶产干
受宠若惊	受宠若惊	受若宠惊	受仰着惊	高尔夫球[1]	仰若宠着
年复一年	年复一年	年一复年	年饭粮年	意想不到	饭一复粮
难以置信	难以置信	难置以信	难东庙信	人寿保险	东置以庙
一窍不通	一窍不通	一不窍通	一稍时通	担惊受怕	稍不窍时
史无前例	史无前例	史前无例	史肢下例	一般来说	
一事无成	一事无成	一无事成	一细柔成	隐姓埋名	
电话会议	电话会议	电会话议	电摸开议	谢天谢地	
并肩作战	并肩作战	并作肩战	并锯工战	另一方面	
到此为止	到此为止	到为此止	到消降止	闭路电视	
坐以待毙	坐以待毙	坐待以毙	坐此住毙	无拘无束	
指手画脚	指手画脚	指画手脚	指丧权脚	一厢情愿	
辛辛苦苦	辛辛苦苦	辛苦辛苦	辛善端苦	罪魁祸首	
以防万一	以防万一	以万防一	以解军一	第三世界	
起死回生	起死回生	起回死生	起长父生	彻头彻尾	
活蹦乱跳	活蹦乱跳	活乱蹦跳	活婚宅跳	得寸进尺	
无精打采	无精打采	无打精采	无牵于采	提心吊胆	
相提并论	相提并论	相并提论	相外核论	以牙还牙	
容光焕发	容光焕发	容焕光发	容备防发	从天而降	
众所周知	众所周知	众周所知	众跌退知	赴汤蹈火	
蒙在鼓里	蒙在鼓里	蒙鼓在里	蒙口记里	一臂之力	
十字路口	十字路口	十路字口	十附卧口	习以为常	
自找麻烦	自找麻烦	自麻找烦	自茶局烦	不仅如此	
危在旦夕	危在旦夕	危旦在夕	危悲催夕	迄今为止	
逍遥法外	逍遥法外	逍法遥外	逍原轴外	自然而然	
不同寻常	不同寻常	不寻同常	不相视常	发号施令	
打草惊蛇	打草惊蛇	打惊草蛇	打球具蛇	不管怎样	
出乎意料	出乎意料	出意乎料	出盘出料	翻翻实实	
无线电话	无线电话	无电线话	无相效话	死里逃生	
惊慌失措	惊慌失措	惊失慌措	惊割心措	善解人意	
公共场所	公共场所	公场共所	公应手所	职业道德	
生物学家	生物学家	生学物家	生弑身家	四分之一	
大干一场	大干一场	大一干场	大实货场	说三道四	
出人头地	出人头地	出头人地	出落户地	千里迢迢	
无关紧要	无关紧要	无紧关要	无抵灭要	全心全意	
至关重要	至关重要	至重关要	至照效要	白马王子	
整装待发	整装待发	整待装发	整灯口发	轻而易举	
人际关系	人际关系	人关际系	人出服系	种族歧视	
名副其实	名副其实	名其副实	名病室实	一清二楚	
融为一体	融为一体	融一为体	融缘巧体	亚历山大	
重蹈覆辙	重蹈覆辙	重覆蹈辙	重失赃辙	前所未有	
开诚布公	开诚布公	开布诚公	开习法公	各种各样	
共产主义	共产主义	共主产义	共家兵义	莎士比亚	
不顾一切	不顾一切	不一顾切	不戒入切	无可奉告	
百万富翁	百万富翁	百富万翁	百轻写翁	游手好闲	
重操旧业	重操旧业	重旧操业	重假于业	例行公事	
出类拔萃	出类拔萃	出拔类萃	出受涨萃	为所欲为	
绳之以法	绳之以法	绳以之法	绳水态法	天主教徒	
毫不留情	毫不留情	毫留不情	毫理石情	孤注一掷	
一见钟情	一见钟情	一钟见情	一国梁情	自暴自弃	

(*Appendix continues*)

Appendix (*continued*)

	Condition				
Target	Repetition prime	TC prime	Classic SC prime	Unrelated prime	External SC prime
自作聪明	自作聪明	自聪作明	自用军明	脱口而出	
自由主义	自由主义	自主由义	自自渍义	身无分文	
引人注目	引人注目	引注人目	引名物目	无与伦比	
平安无事	平安无事	平无安事	平阅礼事	与此同时	
不知所措	不知所措	不所知措	不法教措	扪心自问	
无济于事	无济于事	无于济事	无实场事	循规蹈矩	
华而不实	华而不实	华不而实	华抗党实	小道消息	
改过自新	改过自新	改自过新	改亏尽新	飘飘欲仙	
迫不及待	迫不及待	迫及不待	迫世境待	动手动脚	
毋庸置疑	毋庸置疑	毋置庸疑	毋顺说疑	从那之后	
夜以继日	夜以继日	夜继以日	夜退乡日	言归正传	
特种部队	特种部队	特部种队	特亏事队	鸡毛蒜皮	
奥林匹克	奥林匹克	奥匹林克	奥惧于克	有朝一日	
随心所欲	随心所欲	随所心欲	随多题欲	实实在在	
不可收拾	不可收拾	不收可拾	不应讨拾	从头到尾	
化学反应	化学反应	化反学应	化年表应	有生之年	
若无其事	若无其事	若其无事	若折销事	一败涂地	
不过如此	不过如此	不如过此	不上骗此	澳大利亚	
无名小卒	无名小卒	无小名卒	无对板卒	食物中毒	
训练有素	训练有素	训有练素	训流用素	雄心壮志	
置之不理	置之不理	置不之理	置寒灾理	进进出出	
与众不同	与众不同	与不众同	与石牢同	心平气和	
大惊小怪	大惊小怪	大小惊怪	大盗案怪	感情用事	
一席之地	一席之地	一之席地	一促短地	惨不忍睹	
无稽之谈	无稽之谈	无之稽谈	无水笼谈	臭名昭着	
非同寻常	非同寻常	非寻同常	非遇合常	卷土重来	
正当防卫	正当防卫	正防当卫	正叮附卫	巡回演出	
哺乳动物	哺乳动物	哺动乳物	哺精实物	五角大楼	
世界大战	世界大战	世大界战	世心眉战	单枪匹马	
洗耳恭听	洗耳恭听	洗恭耳听	洗测象听	自欺欺人	
一无所有	一无所有	一所无有	一牵上有	逃之夭夭	
无家可归	无家可归	无可家归	无奋命归	简而言之	
孤身一人	孤身一人	孤一身人	孤纳下人	隐形眼镜	
蛛丝马迹	蛛丝马迹	蛛马丝迹	蛛调备迹	死路一条	
脱颖而出	脱颖而出	脱而颖出	脱存养出	爱因斯坦	
梦想成真	梦想成真	梦成想真	梦接议真	想方设法	
安然无恙	安然无恙	安无然恙	安作端恙	基督教徒	
防弹背心	防弹背心	防背弹心	防上战心	不择手段	
后会有期	后会有期	后有会期	后军灾期	有限公司	
梦寐以求	梦寐以求	梦以寐求	梦怠步求	当务之急	
本职工作	本职工作	本工职作	本出落作	大喊大叫	
完好无损	完好无损	完无好损	完转途损	婆婆妈妈	
严阵以待	严阵以待	严以阵待	严枪标待	精疲力尽	
不可思议	不可思议	不思可议	不白挨议	长话短说	
守口如瓶	守口如瓶	守如口瓶	守授兵瓶	翻天覆地	
尽力而为	尽力而为	尽而力为	尽求智为	水落石出	
轻举妄动	轻举妄动	轻妄举动	轻调台动	似曾相识	

Note. All these stimuli were used in Experiment 1. The first half of the stimuli was used in Experiment 2. The first 100 stimuli were used in Experiment 3. The second half of the stimuli was used in Experiment 4. Note that the external controlled condition for the transposition condition (SC) primes were only used in Experiment 3.

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