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# On the flexibility of letter position coding during lexical processing: Evidence from eye movements when reading Thai

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Previous research supports the view that initial letter position has a privileged role in comparison to internal letters for visual-word recognition in Roman script. The current study examines whether this is the case for Thai. Thai is an alphabetic script in which ordering of the letters does not necessarily correspond to the ordering of a word's phonemes. Furthermore, Thai does not normally have interword spaces. We examined whether the position of transposed letters (internal, e.g., porblem, vs. initial, e.g., rpoblem) within a word influences how readily those words are processed when interword spacing and demarcation of word boundaries (using alternating**bold** text) is manipulated. The eye movements of 54 participants were recorded while they were reading sentences silently. There was no apparent difference in degree of disruption caused when reading initial and internal transposed-letter nonwords. These findings give support to the view that letter position encoding in Thai is relatively flexible and that actual identity of the letter is more critical than letter position. This flexible encoding strategy is in line with the characteristics of Thai—that is, the flexibility in the ordering of the letters and the lack of interword spaces, which creates a certain level of ambiguity in relation to the demarcation of word boundaries. These findings point to script-specific effects operating in letter encoding in visual-word recognition and reading.

*Keywords*: Eye movements; Interword spaces; Reading; Thai; Transposed letter effects; Visual word recognition.

There has been much debate about the relative importance of letter identity and letter position in visual-word recognition and reading. Research using transposition letter effects across different orthographies indicates that there is quite a degree of flexibility in the coding of letter position

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(see O'Connor & Forster, 1981; Perea & Carreiras, 2006; Perea & Lupker, 2004; Schoonbaert & Grainger, 2004, on Roman script—English, French, Basque, and Spanish, respectively; see Perea, Nakatani, & van Leeuwen, 2011, on Japanese kana script; see Velan & Frost, 2011, on Hebrew script; see Perea, Abu-Mallouh, García-Orza, & Carreiras, 2011, on Arabic script; see Lee & Taft, 2009, on Korean Hangul script).

Research on Roman script supports the view that the initial external letter position has a privileged role for word recognition in comparison to internal letters (e.g., Chambers, 1979; Estes, Allmeyer, & Reder, 1976; Gómez, Ratcliff, & Perea, 2008; Jordan, Patching, & Thomas, 2003; Perea, 1998; Rayner & Kaiser, 1975; White, Johnson, Liversedge, & Rayner, 2008). Consistent with this view, transposed-letter effects in Indo-European languages tend to be small or negligible when the initial letter is involved. For instance, in the context of masked priming experiments, Perea and Lupker (2007) with Spanish stimuli, Kinoshita, Castles, and Davis (2009) with English stimuli, and Schoonbaert and Grainger (2004) failed to find a significant masked transposed-letter priming effect in lexical decision when the initial letter was involved (see also Gómez et al., 2008, for a similar finding with a perceptual identification task in English). Taken together, these findings are consistent with the importance of the initial letter in the Roman script.

Not surprisingly, all the recently proposed computational models of visual-word recognition—which have been originally tested with stimuli from Indo-European languages (and the Roman script)—assume that the initial letter position plays a privileged role during the process of lexical access. For instance, the SERIOL model (Whitney, 2001) assumes that word-initial initial letters "have the highest activations" and are less susceptible to noise. In the overlap model (Gómez et al., 2008), there is a degree of perceptual uncertainty associated with each letter position, and perceptual noise is more reduced for the initial letter position than for other letter positions (see Gómez et al., 2008, Figure 14). As an illustration, *jugde* closely resembles *judge*, while *ujdge* does not. A similar reasoning applies to other models of visual-word recognition; for instance, in Davis's (2010) spatial coding model, there is a dynamic end-letter marking in which "the identification of the initial letter channel triggers the beginning of the coding cycle" (p. 718).

But is the importance of the initial letter position a universal phenomenon? In a recent lexical decision experiment, Perea, Winskel, and Ratitamkul (in press) found a significant masked transposed-letter priming effect in Thai when the initial letter was transposed even in very short words (e.g., าบท–บาท was faster than พะท–บาท; transposed-letter condition vs. replacement-letter condition). This suggests that the role played by the initial letter in Thai may not be as critical as in Indo-European languages and that letter position coding in Thai is very flexible. Perea et al. (in press) indicated two reasons why Thai may be particularly flexible with respect to letter position coding. First, several vowels (i.e., เ_ /e:/, แ_ /ɛ:/, โ_ /o:/, ไ_ /aj/, ใ_ /aj/) precede the consonant in writing but follow it in speech (e.g., แบน /ɛ:bn/'flat' is spoken as /bɛ:n/), whereas other vowels are spoken in the order that they are written (e.g., บาท /ba:t/ "Baht" is spoken as /ba:t/; see Winskel, 2009)—this implies that position coding in Thai needs to be flexible enough so that readers may appropriately encode the letter positions of words with or without these misaligned vowels. Secondly, the Thai script does not have interword spaces, which implies that during normal reading there is a degree of ambiguity in relation to which word a given letter belongs to (an example in English: thereisadegreeofambiguitywheninterwordspacesarenotavailable; see also Perea, Nakatani, et al., 2011, for a similar argument with respect to mora position coding in Japanese kana, another unspaced language).

The above-cited results from Perea et al. (in press) were obtained using a laboratory word identification task (i.e., lexical decision), and one obvious question is whether these findings can be extended to normal reading using a more ecologically valid procedure. In addition, one potential limitation of the Perea et al. (in press) experiment is that they only tested initial transpositions, so that it remains unanswered whether letter position plays a role in transposed-letter effects in Thai (e.g., it could be the case that internal transpositions would produce greater priming effects than initial transpositions). In order to examine the importance of initial letter position in Thai, we investigated whether the position of transposed letters (initial vs. internal) within a word influences how readily those words are processed during normal silent reading. This enables us to examine whether the importance of initial letter position in visual-word recognition is a universal or a more script-specific phenomenon.

As stated above, the coding of letter position has been found to be quite flexible across different orthographies. Although most of the evidence comes from laboratory word identification tasks (e.g., using the masked priming paradigm), there is also empirical evidence of transposition effects during normal silent reading when using parafoveal previews instead of foveally presented primes, in particular for internal letter positions (e.g., see Johnson, 2007; Johnson, Perea, & Rayner, 2007). This research suggests that letter identity information plays a prominent role relative to letter position information in lexical access and word identification during normal silent reading. In order to investigate flexibility of letter position encoding and if external or internal letters are more easily encoded during normal silent reading, White et al. (2008) recorded eye movements as participants read English sentences with words with transpositions involving either internal (e.g., *porblem*) or external (e.g., *rpoblem*) letters. As well as the target word, all words with five or more letters within the sentence were transposed. They found, from both global and local measures, that there was greater disruption to reading with external transpositions than with internal transpositions. This supports the view that external letters are more critical for word recognition than internal letters—as proposed by the models of visual-word recognition. In the current study we compared initial versus internal letter position in Thai. We did not focus on final external letter position, as results for final letter position are less consistent than those involving the initial letter position (see Gómez et al., 2008; Whitney, 2001, for review).

In the current study, we also take advantage of one distinctive feature of Thai: Unlike English, Thai sentences are normally written without interword spaces. Not surprisingly, reading is substantially slowed down when interword spaces are removed from English sentences. Both the way the eyes move through the text and the word identification process are substantially disrupted, as reflected by eye movement measures (Morris, Rayner, & Pollatsek, 1990; Pollatsek & Rayner, 1982; Rayner, Fischer, & Pollatsek, 1998; Spragins, Lefton, & Fischer, 1976). Typically, when reading normal spaced text in Indo-European languages, readers tend to land a bit to the left of the middle of the word (the preferred viewing position, PVP), whereas when spaces are removed, reading is disrupted, and readers tend to land closer to the beginning of the word (Rayner et al., 1998). Interword spaces form clear parafoveal word segmentation cues so that saccades can be targeted to land close to the PVP. In a previous study on Thai, Winskel, Radach, and Luksaneeyanawin (2009) examined the eye movements of participants reading target words in sentences with and without interword spaces. There was support for a facilitatory function of interword spaces as word processing (as reflected in gaze duration and total viewing duration) was facilitated but eye guidance (word targeting and lexical segmentation) was not facilitated (or disrupted) by insertion of interword spaces. In a recent study, Bai, Yan, Liversedge, Zang, and Rayner (2008) investigated whether word units rather than individual characters are of primary importance when reading Chinese, which also does not have interword spaces. They found that sentences with an unfamiliar word-spaced format were as easy to read as visually familiar unspaced text. They also used an innovative technique in their second experiment, which involved highlighting word boundaries rather than inserting spaces. Demarcating word boundaries, either through the use of spaces or highlighting, neither hindered nor facilitated reading in Chinese. In contrast, Perea and Acha (2009) found that, in a spaced language (Spanish), providing visual cues for word boundaries (via an alternating**bold** manipulation) facilitated reading in comparison to the unspaced condition and resulted in only a small reading cost relative to standard, spaced text. In the current study, we use a similar technique as used by Bai et al. (2008) and Perea and Acha (2009). More specifically, in the present experiment, we tested whether any potential advantage of the initial letter position in an unspaced alphabetic language (Thai) is due to visual cues—we did so by manipulating interword spacing and demarcation of word boundaries. We demarcated word boundaries by highlighting words using an alternating**bold** manipulation (see Perea & Acha, 2009; e.g., โรงเรียน**จัด**การ**ประกวด**วาด**ภาพ**).

In sum, in the present experiment, participants were presented intact sentences, sentences containing a nonword created by transposing the initial letters, and sentences containing a nonword created by transposing two internal letters, while their eye movements were monitored. Furthermore, each sentence was presented unspaced (as is normal for Thai), unspaced but with an alternating**bold** manipulation, or with spaces between words. The predictions of the experiment are clear. First, we expect greater disruption for transposed words than for the control words. Secondly, if word-initial letters are more critical for word recognition than internal letters regardless of the script (i.e., if the advantage of the initial letter is a universal phenomenon), then we can expect initial transpositions in Thai to be more disruptive to reading than internal transpositions. Moreover, as letter encoding occurs early in lexical identification, we can expect differences between initial and internal transpositions to become apparent early in the temporal processing of target words when reading, as happens in English (see White et al., 2008). Alternatively, as suggested from the masked priming data in Perea et al. (in press), the role played by the initial letter in Thai may not be as critical as in Indo-European languages. Consequently, the differences between initial and internal transpositions would be (to some degree) similar. This latter outcome would support a script-specific view of visual word recognition.

Finally, if lateral masking between letters plays a role in the coding of letter position in Thai, transposition effects should be modulated by the spacing manipulation, such that in the normal unspaced and alternating**bold** conditions, there will be no difference between initial and internal transposed letter (TL) effects, whereas in the spaced condition with less lateral inhibition on the initial transpositions we can expect less reading cost on internal than on initial transpositions—as occurs in spaced English sentences (see White et al., 2008). Alternatively, if both spaced and alternating**bold** text produce shorter reading times for initial transpositions than does unspaced text, this would highlight the importance of higher order top-down processes.

## Method

### *Participants*

Fifty-four students and staff were recruited from Chulalongkorn University, Bangkok, Thailand and were tested at the Center for Research in Speech and Language Processing (CRSLP). Participants all had normal or corrected-to-normal vision and were paid to participate in the experiment. All were naive as to the purpose of the experiment.

### *Apparatus*

The eye movements of the participants were recorded with an EyeLink 1000 eye tracker manufactured by SR Research Ltd (Canada). The sampling rate was set at 2000 Hz. The sentences were presented on a 21-inch ViewSonic P227f monitor with the characters presented in Thai Courier Proportional font size 14. Approximately 3 characters subtended 1 degree of visual angle. A chin and forehead rest was utilized to minimize head movements. Viewing was binocular, although only data from the right eye were analysed. The sentences were displayed at a viewing distance of 70 cm.

### *Materials and design*

The experimental design was a 3 (type of transposition: control, internal, initial) × 3 (spacing: normal unspaced, alternating**bold**, spaced). Nine lists of 72 sentences were constructed. There were 24 sentences in each of the three different conditions: unspaced, spaced, alternating**bold**. The sentences were counterbalanced across the nine lists, so that the corresponding control words, internal, and initial TL nonwords were included in all conditions. The items were counterbalanced so that no participant saw any critical word more than once. Six participants completed each of the nine different lists. The sentences were presented in a fixed pseudorandom order, with 8 filler sentences presented at the beginning of each list.

The target words were 5 and 6 letters in length. All letter transpositions in the experiment involved C–C and C–V (where C = consonant, V = vowel) exchanges (see Lupker, Perea, & Davis, 2008). None of the transpositions produced real words, and all of the transpositions produced a change in spelling. The target words/nonwords were always positioned around the middle of nonpredictable sentences.

In order to ensure that the TL nonword test stimuli selected in the current study could be correctly identified, a rating task of test sentences was conducted. Three different lists of sentences with the TL stimuli were created consisting of 110 sentences in each list in the normal unspaced format. For each item, 9 participants completed each of the three different lists. The lists also included 18 filler sentences that contained nonwords. Participants who did not participate in the eye movement experiment read the sentences and rated them in terms of how easily they could understand the sentences using a Likert scale with "1" representing "very easy to understand" to "7" representing "can't understand at all". The 72 test sentences were selected on the basis that the TL nonwords could be readily identified by participants with means on the rating task of less than or equal to 2.

Sample sentences of the different manipulations are shown in Table 1. In the control condition, the items were spelled correctly (e.g., ประเทศ /prathe:t/ "country"). Transpositions were always adjacent and were either internal (e.g., ปะรเทศ /parthe:t/) involving the second and third letters or initial (e.g., รปะเทศ /rpathe:t/) involving the first and second letters. The mean target word frequency was 144 per million (calculated using the Thai one million word database; Luksaneeyanawin, 2004).

*Procedure*

Participants were asked to carefully read the sentences for comprehension. They were instructed that some sentences might be strange as the spacing between words varied, and some words were in bold text. In addition, some words in the sentences had spelling mistakes. Regardless of this, they were to continue reading for comprehension. In addition, in order to ensure

**Table 1.** *Example of the different spacing and target word TL manipulations*

| *Spacing* | *Transposition type* | *Example* |
|---|---|---|
| Normal unspaced | Control | เกิดเป็นคนไทยควรสำนึกในบุญคุณของประเทศโดยการประพฤติตนเป็นคนดี<br>Born as a Thai, (one) should feel indebted to the country (and repay) by behaving as a good citizen |
| | Internal | เกิดเป็นคนไทยควรสำนึกในบุญคุณของปะรเทศโดยการประพฤติตนเป็นคนดี |
| | Initial | เกิดเป็นคนไทยควรสำนึกในบุญคุณของรปะเทศโดยการประพฤติตนเป็นคนดี |
| Alternating**bold** | Control | เกิด**เป็น**คนไทย**ควรสำนึก**ใน**บุญคุณ**ของ**ประเทศ**โดย**การ**ประพฤติตน**เป็น**คน**ดี** |
| | Internal | เกิด**เป็น**คนไทย**ควรสำนึก**ใน**บุญคุณ**ของ**ปะรเทศ**โดย**การ**ประพฤติตน**เป็น**คน**ดี** |
| | Initial | เกิด**เป็น**คนไทย**ควรสำนึก**ใน**บุญคุณ**ของ**รปะเทศ**โดย**การ**ประพฤติตน**เป็น**คน**ดี** |
| Spaced | Control | เกิด เป็น คนไทย ควรสำนึก ใน บุญคุณ ของ ประเทศ โดย การประพฤติตน เป็น คน ดี |
| | Internal | เกิด เป็น คนไทย ควรสำนึก ใน บุญคุณ ของ ปะรเทศ โดย การประพฤติตน เป็น คน ดี |
| | Initial | เกิด เป็น คนไทย ควรสำนึก ใน บุญคุณ ของ รปะเทศ โดย การประพฤติตน เป็น คน ดี |

*Note:* TL = transposed letter. The target words/nonwords are underlined. Control: ประเทศ/prathe:t/"country". TL internal: ปะรเทศ/parth:t/. TL initial: รปะเทศ/rpathe:t/.

comprehension, 20% of the sentences were followed by comprehension questions. The mean error rate on the comprehension questions was 2%, indicating that participants had carefully read and understood the sentences. The comprehension rates did not differ across conditions.

After the calibration and validation process, participants read eight practice sentences. They then proceeded to the experimental phase. Each trial started with the presentation of a fixation point that coincided with the location of the first letter of the test sentence. The eye tracker was checked and recalibrated if necessary prior to the presentation of each sentence. After reading each sentence, participants pressed a response button that recorded sentence reading response times. The experiment lasted about 20 min. On completion of the experiment, participants were asked whether there were any words that they did not understand in any of the sentences. All participants reported that they could read all the words in the sentences and that there were no words that they could not understand.

### *Analyses*

Across all trials, 3% of trials were excluded due to tracker loss and zero reading times on the first part of the sentence. Fixations under 80 ms that were within one letter of the next or previous fixation were incorporated into that fixation. Fixations under 80 ms and over 1,200 ms were discarded. In order to investigate the effect of spacing on transposition type, a series of 3 (transposition type: control, internal, initial) × 3 (spacing: normal unspaced, alternating**bold**, spaced) analyses of variance (ANOVAs) based on participant and item variability were conducted.

## Results

The results were analysed in terms of global and local measures. Global measures were based on measures at the sentence level. A global analysis was conducted in order to provide an insight into the general effects of the spacing manipulation. Local measures were based on only the critical TL target word/nonword. In the analyses in which we kept the null hypothesis of a critical effect (or interaction), we computed the probability of the null hypothesis being true, given the obtained data, $p(H_0|D)$ (Wagenmakers, 2007; see also Masson, 2011). It has been claimed that positive evidence that the null hypothesis is true given the obtained data occurs when $p(H_0|D) > .75$, while strong evidence is obtained with probability values above .90 (Masson, 2011; see also Raftery, 1995).

### *Global measures*

Global measures included total sentence reading time and fixation count. There was a main effect of transposed letter type for total sentence reading time, $F_1(2, 53) = 37.40$, $p < .001$, $\eta_p^2 = .414$; $F_2(2, 71) = 5.42$, $p < .01$, $\eta_p^2 = .017$, and fixation count, $F_1(2, 53) = 25.02$, $p < .001$, $\eta_p^2 = .321$; $F_2(2, 71) = 4.09$, $p < .05$, $\eta_p^2 = .013$. Descriptive statistics are presented in Table 2. As expected, sentence reading times were longer, and number of fixations were greater for the internal and initial TL conditions than for the control condition—sentence reading time: internal $t_1(53) = 8.06$, $p < .001$; $t_2(71) = 2.89$, $p < .01$; initial $t_1(53) = 6.93$, $p < .001$; $t_2(71) = 2.89$, $p < .01$; sentence fixation count: internal $t_1(53) = 6.14$, $p < .001$; $t_2(71) = 2.45$, $p < .05$; initial $t_1(53) = 6.25$, $p < .001$; $t_2(71) = 2.54$, $p < .05$. Importantly, there was no significant difference between sentences with internal and initial transpositions—$t$s < 2; sentence fixation count: $p(H_0/D) = .8753$ and .8946 for the participant and item analyses, respectively; sentence reading time: $p(H_0/D) = .8594$ and .8946 for the participant and item analyses, respectively.

There was a significant main effect of spacing for sentence reading time for the participant analysis, $F_1(2, 53) = 4.33$, $p < .05$, $\eta_p^2 = .076$; $F_2(2, 71) = 2.02$, *ns*, and for fixation count, $F_1(2, 53) = 4.11$, $p < .05$, $\eta_p^2 = .072$; $F_2(2, 71) = 3.12$, $p < .05$, $\eta_p^2 = .010$: Sentence reading times were significantly longer for the alternating**bold** (3,340 ms) than for the spaced condition (3,195 ms), $t_1(53) = 2.90$, $p < .01$; $t_2(71) = 2.02$, $p < .05$, but it did not reach significance for unspaced (3,266 ms) in comparison to spaced text, or for unspaced in comparison to alternating**bold** text ($t$s < 2). There were more fixations in the spaced (14.1) than in the unspaced (13.6) condition, $t_1(53) =$

**Table 2.** *Global measures for each of the conditions*

| | *Mean total sentence reading time (in ms)* | | | *Mean total sentence fixation count* | | |
|---|---|---|---|---|---|---|
| *Condition* | *Control* | *Internal TL* | *Initial TL* | *Control* | *Internal TL* | *Initial TL* |
| Unspaced | 3,140 | 3,342 | 3,317 | 13.2 | 13.8 | 13.8 |
| | (865) | (884) | (887) | (3.3) | (3.3) | (3.2) |
| Alternating**bold** | 3,221 | 3,405 | 3,400 | 13.6 | 14.2 | 14.0 |
| | (865) | (768) | (892) | (3.1) | (3.0) | (3.2) |
| Spaced | 3,067 | 3,248 | 3,270 | 13.6 | 14.2 | 14.5 |
| | (781) | (895) | (840) | (3.1) | (3.4) | (3.3) |

*Note:* TL = transposed letter. Standard deviations are in parentheses.

2.95, $p < .01$; $t_2(71) = 2.40$, $p < .05$, but there was only a marginally significant difference between alternating**bold** (13.9) and spaced text for the participant analysis, $t_1(53) = 1.82$, $p = .07$; $t_2(71) = 0.87$, *ns*. We can expect more fixations in the spaced condition than in the unspaced text due to an increase in the spatial distribution of the sentence in the spaced condition in comparison to the unspaced condition (see Figure 1). As there were more fixations for spaced text but overall shorter reading times, fixation durations were shorter on average in this condition. The alternating**bold** and unspaced text conditions were not significantly different (*ts* < 1). Notably, there were no significant interaction effects between transposition type and spacing for either sentence

| Spacing | Transposition type | Example |
|---|---|---|
| Normal unspaced | Control | เกิดเป็นคนไทยควรสำนึกในบุญคุณของประเทศโดยการประพฤติตนเป็นคนดี<br>Born as a Thai, (one) should feel indebted to the country (and repay) by behaving as a good citizen |
| | Internal | เกิดเป็นคนไทยควรสำนึกในบุญคุณของปะรเทศโดยการประพฤติตนเป็นคนดี |
| | Initial | เกิดเป็นคนไทยควรสำนึกในบุญคุณของรปะเทศโดยการประพฤติตนเป็นคนดี |
| Alternating**bold** | Control | เกิด**เป็น**คนไทย**ควรสำนึก**ใน**บุญคุณ**ของ**ประเทศ**โดย**การ**ประพฤติตน**เป็น**คน**ดี** |
| | Internal | เกิด**เป็น**คนไทย**ควรสำนึก**ใน**บุญคุณ**ของ**ปะรเทศ**โดย**การ**ประพฤติตน**เป็น**คน**ดี** |
| | Initial | เกิด**เป็น**คนไทย**ควรสำนึก**ใน**บุญคุณ**ของ**รปะเทศ**โดย**การ**ประพฤติตน**เป็น**คน**ดี** |
| Spaced | Control | เกิด เป็น คนไทย ควรสำนึก ใน บุญคุณ ของ ประเทศ โดย การประพฤติตน เป็น คน ดี |
| | Internal | เกิด เป็น คนไทย ควรสำนึก ใน บุญคุณ ของ ปะรเทศ โดย การประพฤติตน เป็น คน ดี |
| | Initial | เกิด เป็น คนไทย ควรสำนึก ใน บุญคุณ ของ รปะเทศ โดย การประพฤติตน เป็น คน ดี |

**Figure 1**. *Example of the different spacing and target word TL manipulations. The target words/nonwords are underlined.*
1. Control: ประเทศ /prathe:t/ 'country'
2. TL internal: ปะรเทศ /parthe:t/
3. TL initial: รปะเทศ /rpathe:t/

reading time or fixation count—all *F*s $< 1$; sentence reading time: $p(H_0/D) = .9996$ and .9996 for the participant and item analyses, respectively; sentence fixation count: $p(H_0/D) = .9995$ and .9996 for the participant and item analyses, respectively.

### *Local measures*

We calculated the duration of first fixation, gaze duration (the sum of fixations on a word before leaving it), and total fixation duration (the sum of all fixations within a word) on the critical target words. These different measures give information about the temporal processing of the target words/TL-nonwords and how word processing unfolds over time (Juhasz, Inhoff, & Rayner, 2005). First fixation measures are likely to reflect initial letter coding and word recognition processes, whereas the refixation measures of gaze and total fixation durations are likely to reflect later word recognition processes including comprehension and integration at the sentence level (Juhasz et al., 2005; White et al., 2008). Descriptive statistics are presented in Table 3. The total number of target words that were skipped was very low across the different spacing conditions: normal unspaced (14), alternating**bold** (7), and spaced (31).

For first fixation duration, there was a main effect of transposed letter type, $F_1(2, 53) = 27.99$, $p < .001$, $\eta_p^2 = .346$; $F_2(2, 71) = 15.97$, $p < .001$, $\eta_p^2 = .048$. First fixation durations for the control words were significantly shorter than those for the internal, $t_1(53) = 6.81$, $p < .001$; $t_2(71) = 5.13$, $p < .001$, or initial, $t_1(53) = 6.41$, $p < .001$; $t_2(71) = 4.98$, $p < .001$, TL nonwords. There was no significant difference between first fixation durations for internal and initial TL nonwords: *ts* $< 1$, $p(H_0/D) = .8773$ and .8946 for the participant and item analyses, respectively. Furthermore, there was no significant effect of spacing, $F_1(2, 53) = 2.15$, *ns*, $p(H_0/D) = .9654$; $F_2(2, 71) = 1.47$, *ns*, $p(H_0/D) = .9839$, or an interaction effect between transposed letter type and spacing, $F_1(2, 53) = 1.19$, $p = .32$, $p(H_0/D) = .9994$; $F_2(2, 71) = 0.85$, $p = .50$, $p(H_0/D) = .9998$.

For gaze duration and total fixation duration, there was a main effect of transposed letter type—gaze duration: $F_1(2, 53) = 66.86$, $p < .001$, $\eta_p^2 = .558$; $F_2(2, 71) = 41.34$, $p < .001$, $\eta_p^2 = .116$; total fixation duration: $F_1(2, 53) = 84.69$, $p < .001$, $\eta_p^2 = .615$; $F_2(2, 71) = 79.21$, $p < .001$, $\eta_p^2 = .201$. Gaze duration and total fixation duration were shorter for control words than for internal and initial transpositions—gaze duration: internal $t_1(53) = 10.36$, $p < .001$; $t_2(71) = 7.85$, $p < .001$; initial $t_1(53) = 10.27$, $p < .001$; $t_2(71) = 8.48$, $p < .001$; total fixation duration: internal $t_1(53) = 11.85$, $p < .001$; $t_2(71) = 11.23$, $p < .001$; initial $t_1(53) = 10.21$, $p < .001$; $t_2(71) = 11.10$, $p < .001$. There was no significant difference between internal and initial TL conditions for either gaze duration or total fixation duration—*ts* $< 2$; gaze duration: $p(H_0/D) = .8584$ and $p(H_0/D) = .8944$ for the participant and item analyses, respectively; total fixation duration: $p(H_0/D) = .8784$ and $p(H_0/D) = .8946$, for the participant and item analyses, respectively.

**Table 3.** *Local measures for each of the conditions*

| | *First fixation duration* | | | *Gaze duration* | | | *Total fixation duration* | | |
|---|---|---|---|---|---|---|---|---|---|
| *Conditions* | *Control* | *Internal TL* | *Initial TL* | *Control* | *Internal TL* | *Initial TL* | *Control* | *Internal TL* | *Initial TL* |
| Unspaced | 241 | 268 | 269 | 357 | 467 | 445 | 412 | 577 | 552 |
| | (44) | (49) | (58) | (99) | (139) | (122) | (122) | (199) | (154) |
| Alternating**bold** | 239 | 271 | 267 | 365 | 453 | 474 | 414 | 577 | 557 |
| | (40) | (63) | (54) | (111) | (138) | (131) | (123) | (172) | (164) |
| Spaced | 241 | 253 | 260 | 305 | 384 | 405 | 335 | 474 | 496 |
| | (49) | (51) | (62) | (91) | (122) | (142) | (93) | (166) | (163) |

*Note:* TL = transposed letter. Measures in ms. Standard deviations are in parentheses.

There was an effect of spacing for gaze duration, $F_1(2, 53) = 25.42, p < .001, \eta_p^2 = .324$; $F_2(2, 71) = 16.47, p < .001, \eta_p^2 = .050$, and total fixation duration, $F_1(2, 53) = 28.20, p < .001, \eta_p^2 = .347$; $F_2(2, 71) = 20.25, p < .001, \eta_p^2 = .060$. Gaze and total fixation durations were shorter for the spaced condition than for the alternating**bold**—gaze duration: $t_1(53) = 6.21, p < .001$; $t_2(71) = 5.03, p < .001$; total fixation duration: $t_1(53) = 6.22, p < .001$; $t_2(71) = 5.12, p < .001$—and unspaced conditions—gaze duration: $t_1(53) = 5.71, p < .001$; $t_2(71) = 4.62, p < .001$; total fixation duration: $t_1(53) = 6.33, p < .001$; $t_2(71) = 4.92, p < .001$. There were no interaction effects between transposition type and spacing—gaze duration: $F_1(2, 53) = 1.14, p = .34, p(H_0/D) = .9994$; $F_2(2, 71) = 0.63, p = .64, p(H_0/D) = .9998$; total fixation duration: $F_1(2, 53) = 0.85, p = .50, p(H_0/D) = .9994$; $F_2(2, 71) = 0.68, p = .61, p(H_0/D) = .9998$. In the spaced text reading times, there were small numerical differences between internal and initial transpositions, which could result from reduced lateral masking for word-initial letters.

The probability of refixating the different transposed letter types was also analysed. There was a significant effect of transposition type, $F_1(2, 53) = 10.87, p < .001, \eta_p^2 = .295$; $F_2(2, 71) = 7.84, p < .001, \eta_p^2 = .024$. The probability of refixating the control word ($M = .86$, $SD = .18$) was significantly less than that for either the internal ($M = .97$, $SD = .21$), $t_1(53) = 4.22, p < .001$, $t_2(71) = 3.77, p < .001$, or the initial ($M = .97$, $SD = .23$), $t_1\ (53) = 3.81, p < .001$, $t_2(71) = 3.38, p = .001$, transpositions. The refixation probabilities were not significantly different for internal and initial transpositions: $ts < 1$, $p(H_0/D) = .8550$ and .8798 for participant and item analyses, respectively. These results are in line with the results for the fixation measures. There was no significant effect of spacing, $Fs < 1, p(H_0/D) = .9733$ and .9812 for participant and item analyses, respectively, or an interaction effect between transposition type and spacing, $Fs < 1$, $p(H_0/D) = .9996$ and .9997 for participant and item analyses, respectively.

In sum, as expected, the control (intact) words were read more easily than the TL nonwords, and this was reflected in all fixation measures. In relation to spacing, there was no significant effect for first fixation duration. For gaze and total fixation duration, spaced text facilitated reading in comparison to both the alternating**bold** and unspaced normal format for words and nonwords. Importantly, internal and initial transpositions were not significantly different, and there was no interaction effect between transposition type and spacing.

### *Initial landing position*

In order to examine the effects of letter transpositions and spacing on oculomotor control, initial first fixation landing position patterns were examined (see Table 4). The initial landing positions on the TL target word stimuli in the different spacing conditions were assessed. There was an effect of transposition word type, $F_1(2, 53) = 4.49, p < .05, \eta_p^2 = .078$; $F_2(2, 71) = 5.72, p < .01, \eta_p^2 = .020$. Control words had initial landing positions closer to midword position than did initial transposed letter words, $t_1(53) = 2.83, p < .01$; $t_2(71) = 3.28, p < .01$. However, there were no significant differences between control words and internal TL nonwords, $ts < 2$, $p(H_0/D) = .7318$ and .8778, or between initial and internal TL nonwords, $ts < 2$, $p(H_0/D) = .8234$ and .8777 for participant and item analyses, respectively.

There was a significant main effect of spacing, $F_1(2, 53) = 45.51, p < .001, \eta_p^2 = .462$; $F_2(2, 71) = 40.73, p < .001, \eta_p^2 = .114$. Planned

**Table 4.** *Initial landing position for transposition and spacing type*

| | *Control* | *Internal TL* | *Initial TL* |
|---|---|---|---|
| Unspaced | –0.73 | –0.82 | –0.90 |
| | (0.47) | (0.49) | (0.50) |
| Alternating**bold** | –0.72 | –0.85 | –0.82 |
| | (0.49) | (0.50) | (0.54) |
| Spaced | –0.30 | –0.31 | –0.50 |
| | (0.53) | (0.50) | (0.46) |

*Note:* TL = transposed letter. Initial landing position is given as distance from midword position in tenths of a letter. Standard deviations are in parentheses.

contrasts revealed that initial landing position was significantly closer to the word centre in the spaced than in the unspaced, $t_1(53) = 8.67$, $p < .001$; $t_2(71) = 7.90$, $p < .001$, or alternating-**bold**, $t_1(53) = 7.52$, $p < .001$; $t_2(71) = 7.36$, $p < .001$, conditions. There was no significant difference in initial landing position between unspaced and alternating**bold** text: $ts < 1$, $p(H_0/D) = .8524$ and .8795 for participant and item analyses, respectively. In the spaced condition, the mean landing position ranged from 0.3 to 0.5 of a letter from the midword position, whereas in the unspaced and alternating**bold**, landing position ranged from 0.7 to 0.9 of a letter from the word centre, which is closer to the beginning of the word. There was no interaction effect between transposition type and spacing, $Fs < 2$, $p(H_0/D) = .9993$ and .9997 for participant and item analyses, respectively.

### *Parafoveal-on-foveal and spillover effects*

In order to more fully investigate the time course of letter transposition effects, parafoveal-on-foveal and spillover effects (i.e., reading times on $n - 1$ and $n + 1$) were examined (see Table 5). There was no evidence of parafoveal-on-foveal effects on word $n - 1$ as evidenced by first fixation duration, $Fs < 1$, $p(H_0|D) = .9775$ and .9658 for participants and items, respectively, or gaze duration, $Fs < 1$, $p(H_0|D) = .9781$ and .9816 for participants and items, respectively. However, there was evidence of spillover effects on word $n + 1$ for first fixation duration for participants, $F_1(2, 53) = 3.07$, $p = .05$, $\eta_p^2 = .055$, and marginally so for items, $F_2(2, 71) = 2.42$, $p = .09$, $\eta_p^2 = .008$. There was a larger spillover effect for internal transpositions than for control words, $t_1(53) = 2.77$, $p < .01$; $t_2(71) = 2.04$, $p < .05$, and which was marginally significantly longer in duration than initial transpositions for participants, $t_1(53) = 1.77$, $p = .08$; $t_2(71) = 1.46$, $p > .1$. There was no significant effect for gaze duration, $Fs < 1$, $p(H_0|D) = .9808$ and .9817 for participants and items, respectively. This indicates that greater disruption to reading was caused by the internal than by control words and to some extent than by initial letter transpositions.

The proportion of regressions made out of word $n + 1$ on first pass was also analysed. There was a significant effect of transposition type, $F_1(2, 53) = 17.97$, $p < .001$, $\eta_p^2 = .253$; $F_2(2, 71) = 20.40$, $p < .001$, $\eta_p^2 = .061$. The proportion of regressions in relation to the critical control word ($M = .09$, $SD = .09$) was significantly less than that for either the internal ($M = .19$, $SD = .15$), $t_1(53) = 4.96$, $p < .001$, $t_2(71) = 6.40$, $p < .001$, or initial ($M = .17$, $SD = .12$), $t_1$ $(53) = 4.40$, $p < .001$, $t_2(71) = 4.39$, $p = .001$, critical word transpositions. The proportion of regressions was not significantly different for internal and initial transpositions, $ts < 1$, $p(H_0/D) = .7996$ and .8463 for participant and item analyses, respectively. There was no significant effect of spacing, $Fs < 1$, $p(H_0/D) = .9818$ and .9862 for participant and item analyses, respectively, or an interaction effect between transposition type and spacing, $Fs < 1$, $p(H_0/D)= .9659$ and .9791 for participant and item analyses, respectively.

**Table 5.** *Effects of letter transpositions of the critical target word on word n − 1 and n + 1 measures*

| *Measures* | *Control* | *Internal TL* | *Initial TL* |
|---|---|---|---|
| Word $n - 1$ | | | |
| First fixation duration | 237 | 235 | 239 |
| | (48) | (44) | (50) |
| Gaze duration | 287 | 288 | 283 |
| | (56) | (58) | (54) |
| Probability of skipping | .20 | .20 | .21 |
| | (.20) | (.22) | (.22) |
| Word $n + 1$ | | | |
| First fixation duration | 249 | 260 | 251 |
| | (37) | (44) | (47) |
| Gaze duration | 313 | 317 | 313 |
| | (57) | (54) | (64) |
| Probability of skipping | .21 | .20 | .20 |
| | (.24) | (.21) | (.22) |

*Note:* TL = transposed letter. Fixation duration measures are in ms. Standard deviations are in parentheses.

## Discussion

As expected, reading sentences with transposed-letter nonwords in Thai was found to be more difficult than reading words without letter transpositions (see White et al., 2008, for evidence in English). More importantly, in relation to the current study, there was no apparent difference in degree of disruption caused when reading internal and initial transposed-letter nonwords—note that we found compelling evidence that the null hypothesis is true—that is, $p(H_0|D)$ values ranging from .86 to .99; see Wagenmakers, 2007. This pattern of findings is in marked contrast with results found in Roman script where, consistent with prior evidence from other paradigms in Indo-European languages, there is greater disruption caused by initial than by internal transpositions (White et al., 2008). Therefore, these findings on Thai give support to the view that actual identity of the letter is more critical than letter position in Thai—even for the initial letter position. This encoding strategy is in line with the characteristics of Thai—that is, the ordering of the letters that does not necessarily correspond to the ordering of a word's phonemes and the lack of interword spaces, which creates a certain level of ambiguity in relation to the demarcation of word boundaries (see also Perea et al., in press, for evidence with masked priming in Thai). These findings point to orthographic-specific effects operating in letter encoding in visual-word recognition and reading (see Velan & Frost, 2011, for further evidence on how the characteristics of a given language shape the process of lexical access).

It is important to note here two procedural differences between the present experiment and White et al.'s (2008) Experiment 1. In the White et al. experiment, all words 5 letters or longer had transpositions, while in the present experiment, the letter transposition only occurred in the critical target word. Nonetheless, this does not discount or negate our present findings—that is, that a reading cost was found for the transposed-letter nonwords. The critical point here is that this reading cost was similar for initial and internal transpositions. Another difference was that White et al. also manipulated word frequency, and in their experiment, transposition effects were weaker for higher frequency than for low-frequency target words. In the present experiment, using high-frequency target words, we found a robust transposed-letter effect—what happened here is that this effect in Thai was similar in size for initial and internal transpositions.

In relation to the spacing manipulation, we found a facilitatory function of interword spaces on reading in Thai, as reflected by the refixation measures of gaze and total fixation duration, but not for first fixation duration. These results are consistent with results found in a previous study conducted on Thai (Winskel et al., 2009). From this, we can surmise that spacing facilitates later word recognition processes, including comprehension and integration at the sentence level in Thai. We found in the current study that initial landing position was also influenced by spacing, so that landing position was shifted closer to the word centre in the spaced than in the unspaced condition. This contrasts with results found in the previous study (Winskel et al., 2009), where there was no significant difference between landing positions in the spaced and unspaced conditions. The transposed-letter manipulation utilized in the current study appears to have affected eye movement behaviour, so that landing positions on the target words tended to be closer to the beginning of the words in unspaced than in spaced sentences. Thus, it appears that saccadic targeting has been affected by the transposition manipulation in unspaced text but not in spaced text where there are clear segmentation cues. This could be explained in terms of a "magnet" or pull effect on the saccade by the orthographically odd letter sequences (Hyönä, 1995).

Importantly, we did not find support for a lateral masking hypothesis, as we did not find that transposition effects were modulated by the spacing manipulation. There was no significant difference between initial and internal TL effects in the spaced condition—in which theoretically there is less lateral masking on initial letters than on internal letters. We expected to find that when spaces were inserted, there would be a reduction in lateral masking on initial letters, resulting in shorter reading times in spaced in comparison to unspaced text with initial transposed words than with internal transposed words. However, there was very little empirical support for this. In Roman script, it has been hypothesized that there is change or expansion in shape of receptive fields of initial letters in order to optimize processing at the first position in strings of letters (Tydgat & Grainger, 2009, see Figure 12; see also Grainger & van Heuven, 2003). Due to the unspaced nature of Thai script, a similar elongation of receptive field for initial letter position has not occurred; instead, the receptive fields for initial and internal letter positions can be envisaged as similar in shape and size. With experience of reading, presumably, smaller receptive field sizes develop as reading skills become more honed in this extremely crowded letter environment (see Whitney & Marton, 2011, for an alternative view). This parallel processing model is compatible with the view that actual identity of the letter is more critical than letter position in Thai—regardless of letter position (initial vs. internal). Further experiments are required to test the viability of this model for Thai. Thus, the present data support the view that the relative importance of both initial and internal letter positions (not just initial) varies across families of languages (Velan & Frost, 2011). Clearly, most of the research in psycholinguistics has focused on experiments in Indo-European languages, and it is in these languages in which the initial letter position plays a key role during lexical access. The present data demonstrate that this is not the case for Thai. Importantly, other families of languages may not be as sensitive to the initial letter position as Indo-European languages either. This may be the case for Semitic languages (e.g., Hebrew, Arabic), in which the root letters play a key role in lexical access (see Velan & Frost, 2011)—rather than the initial letter/syllable of the Indo-European languages. For instance, Perea, Abu Mallouh, and Carreiras (2010) found that, when the order of the root letters was not altered, the magnitude of masked transposed-letter priming in a Semitic language (Arabic) was similar for initial, internal, and final transpositions. Further research is necessary to determine whether or not this pattern of data with masked priming also generalizes to normal silent reading in Semitic languages.

In order to examine the full time course of transposed-letter effects in Thai, it is important to examine whether the potential disruption of initial versus. internal letter transpositions occurs (a) even before the eye is on the target words and (b) when the eye moves to the following word.[1] The first question is related to whether or not there is some evidence of parallel processing of words in Thai. For instance, one might argue that in order to identify word endings in Thai (i.e., an unspaced orthography), rather than using a flexible letter encoding, there might instead be more parallel processing of words. However, when we examined reading times on word $n - 1$, we did not find evidence of parafoveal-on-foveal effects. With respect to the second issue, note that the data for total fixation times showed a large difference between the transposed and the control conditions. This could be taken to suggest that the transpositions disrupted reading somewhat late in the time course of word processing—which would presumably be reflected in spillover effects. Consistent with this view, we did find spillover effects for first pass fixation durations for internal transpositions in comparison to the control words and marginally so in comparison to initial transpositions. This indicates that internal transpositions caused greater disruption to reading than the control words or initial transpositions. Importantly, this effect was relatively short-lived as gaze duration was not affected. We also found an effect of the transpositions in the critical word on the proportion of regressions made out of word $n + 1$ in comparison with the critical control word. The effect was similar for both internal and initial transpositions. This again indicates that there was a disruptive spillover effect from the transposed letter word to the next word. Interestingly, the spillover effect was accentuated for internal transpositions.

When interword spaces are present, clear visual segmentation cues are available so that boundaries of letter clusters forming lexical entities are readily demarcated (Bai et al., 2008). That is, interword spaces form clear segmentation or word boundary

[1] We thank Sarah White for suggesting these analyses.

cues in the parafovea prior to word fixation. In contrast, when spaces are not present, the extent of the letter cluster forming a word has to be determined using other cues. Experienced Thai readers, presumably, have acquired language-specific or script-specific segmentation knowledge of patterns or rules (Bertram, Pollatsek, & Hyönä, 2004). We should note, however, that we did find that the transposed-letter manipulations interfered with initial landing position on the target stimuli, so that there was a tendency to land closer to the beginning of the nonword in initial transpositions than in the control words. Hence, it appears that saccadic targeting has been affected by the spelling errors occurring in initial word position (White et al., 2008). It appears that due to the disruptive influence of initial letter transpositions in Thai script, there is a compensatory shift in landing position to land closer to the word beginning—this trend did not occur just in the unspaced but also in the spaced condition. These disruptive effects could be due to differences in orthographic familiarity (e.g., Hyönä, 1995; Hyönä & Bertram, 2004; White, 2008; White & Liversedge, 2004) rather than any higher level of word processing.

We also expected the alternating**bold** manipulation to have a facilitatory effect on word segmentation similar to the spaced condition (as occurred in the Perea & Acha, 2009, study with Spanish sentences). However, we found that this manipulation was more similar to the normal unspaced condition than to the spaced condition (as occurred in the Bai et al., 2008, study with Chinese sentences), and it even had a slight deleterious effect on reading in comparison to the spaced condition in the global sentence reading times. The fact that alternating**bold** did not facilitate reading in the same way as spaced text indicates that, unlike what happens in Indo-European languages (see Perea & Acha, 2009), it is not forming as effective a segmentation cue for Thai readers as interword spaces. We believe that, as also occurs when reading Chinese sentences (see Bai et al., 2008), the alternating**bold** manipulation could be disrupting the habitual segmentation patterns and cues used by experienced readers to read Thai.

One relevant question for future research is to find out to what degree the flexibility of the orthographic coding scheme for letter position varies across languages for bilingual individuals. As White et al. (2008), reported there is a clear difference between initial and internal manipulations in English—which is consistent with previous research in Indo-European languages. However, the present experiment has shown that this dissociation does not apply when reading Thai sentences. Thus, it may be important to examine whether Thai-English individuals whose first language is Thai would show, in a parallel experiment in English, a similar pattern for English (i.e., a differential transposed-letter effect for initial and internal letter positions) or whether it would be similar to the data reported here.

In sum, the present experiment has shown that the initial letter position in Thai is not as critical as in Roman script during normal silent reading. Thus, the present data offer further support for the view that the orthographic coding scheme is not universal but rather it is modulated by the specific characteristics of each language (e.g., Velan & Frost, 2011).

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