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Testing the flexibility of the modified receptive field (MRF) theory: Evidence from an unspaced orthography (Thai)

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ABSTRACT

In the current study, we tested the generality of the modified receptive field (MRF) theory (Tydgat & Grainger, 2009) with English native speakers (Experiment 1) and Thai native speakers (Experiment 2). Thai has a distinctive alphabetic orthography with visually complex letters (ฝ ฟ or ผ พ) and nonlinear characteristics and lacks interword spaces. We used a two-alternative forced choice (2AFC) procedure to measure identification accuracy for all positions in a string of five characters, which consisted of Roman script letters, Thai letters, or symbols. For the English speakers, we found a similar pattern of results as in previous studies (i.e., a dissociation between letters and symbols). In contrast, for the Thai participants, we found that the pattern for Thai letters, Roman letters and symbols displayed a remarkably similar linear trend. Thus, while we observed qualified support for the MRF theory, in that we found an advantage for initial position, this effect also applied to symbols (i.e., our data revealed a language-specific effect). We propose that this pattern for letters and symbols in Thai has developed as a specialized adaptive mechanism for reading in this visually complex and crowded nonlinear script without interword spaces.

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1. Introduction

The initial position enjoys an advantage in different paradigms involving words and letter strings when participants are fixating at the central position with the Roman script (see Hammond & Green, 1982; Mason, 1975, for early evidence). This initial-position advantage does not occur with strings of symbols, where accuracy is greatest for the central letter position, but performance declines as the distance from the central letter position increases (e.g., Mason & Katz, 1976; see also Mason, 1982; Hammond & Green, 1982). This letter/symbol dissociation can be readily explained in terms of the modified receptive field (MRF) theory (Tydgat & Grainger, 2009). Tydgat and Grainger (2009) proposed that as children learn to read, they develop a specialized system that is custom-built to handle the very specific nature of letters—keep in mind that letters (but not symbols) activate the putative "visual word form area" in the brain (e.g., see Dehaene et al., 2010).

According to the MRF account, there is a change or expansion in shape of receptive fields of initial letters to optimize processing at the first position in strings of letters, which gives an initial position advantage (see Fig. 12 in Tydgat & Grainger, 2009; see also Grainger & Dufau, 2012). This would not occur with strings of symbols, in which the pattern of data merely reflects a drop in visual acuity. Consistent with this idea, Tydgat and Grainger (2009) conducted a series of two-alternative forced choice (2AFC) experiments with skilled adult readers and found a different serial position function for Roman letters (with a W shape in percent correct) when compared to symbol stimuli (with an inverted V function) (see also Ziegler, Pech-Georgel, Dufau, & Grainger, 2010, for a replication of this pattern with 8–13 year olds—both dyslexics and controls).

Traditionally, letter and word recognition research has focused on Roman script and a small number of European languages, in particular English. However, more recently a growing interest in investigating a broader range of languages and scripts has emerged, which is essential if we are to delineate between universal and orthography-specific processes as well as build more comprehensive and representative universal models of reading (see Frost, 2012, for a recent review). In the current study, we aim to test the generality of the MRF account by using Thai, a language with a distinctive alphabetic orthography, which makes interesting comparisons with other languages that use Roman script. Leaving aside that Thai script is visually complex (e.g., it has many letters that closely resemble each other and share common visual features, e.g., ฝ ฟ or ผ พ, to cite two examples), its vowels have a nonlinear configuration in that they can be written above, below, or to either side of the consonant as full letters or diacritics, and commonly

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combine across the syllable to produce a single vowel or diphthong. The orthographic order of vowels also does not necessarily correspond to the phonological order (e.g., แบน <ɛ:bn> 'flat' is spoken as /bɛ:n/; see Winskel, 2009) (a characteristic it shares with other Brahmi-derived scripts). Tone markers occur above the initial consonant of the syllable or word (e.g., ข้าว /k^hâ:w/ 'rice'). Furthermore, Thai does not normally have interword spaces (similar in this respect with Chinese, Japanese, Lao, Khmer, Tibetan, and Burmese), which implies that during normal reading there is a degree of ambiguity in relation to which word a given letter belongs to (e.g., คุณพ่อของฉันชอบรับประทานอาหารที่มีรสจัด). Thus, the reader has to use other cues besides interword spaces to segment the text into words, such as frequently occurring or salient initial letters or combinations of letters and diacritics (Winskel, Radach, & Luksaneeyanawin, 2009). Due to these combined characteristics, Thai script is relatively dense or crowded and exerts distinct challenges to the child learning to read and spell Thai (Winskel & Iemwanthong, 2010).

There is empirical evidence that shows that the encoding of letters during reading in Thai may not be the same as in the Roman script. In a recent study on Thai, Winskel, Perea, and Ratitamkul (2012) 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) was manipulated. Eye movements were recorded while participants read sentences silently. Unlike the parallel experiment in English—in which the reading cost was greater when the disruption affected the initial letter position (see White, Johnson, Liversedge, & Rayner, 2008), there was no apparent difference in the degree of disruption caused when reading initial and internal transposed-letter nonwords. Thus, the findings of Winskel et al. (2012) point to script-specific effects operating in letter position encoding in visual-word recognition and reading. Importantly, support for a lateral masking hypothesis was not found, as the magnitude of the transposed-letter effects was not modulated by the spacing manipulation: there was no significant difference between initial and internal transposed letter effects in the spaced condition—in which 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. We also expected the alternating**bold** manipulation to have a facilitatory effect on word segmentation similar to the spaced condition (as occurred in the study of Perea & Acha, 2009with Spanish sentences). However, we found that this manipulation was more similar to the normal unspaced condition than the spaced condition, 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 that spaced text, in contrast to what happens in Indo-European languages (see Perea & Acha, 2009), indicates that there are different processes occurring when reading Thai and Roman script. Winskel et al. (2012) hypothesized that it could be that the alternating**bold** demarcation of the text is disrupting the habitual segmentation patterns and cues used by experienced readers to read Thai—as occurs when reading Chinese sentences (see also Bai, Yan, Liversedge, Zang, & Rayner, 2008).

In the current study, we used a similar two-alternative forced choice procedure as Tydgat and Grainger (2009), to measure identification accuracy for all positions in a string of five characters, which consisted of Roman script letters, Thai letters, or symbols. Participants were English native speakers (Experiment 1) and Thai native speakers (Experiment 2)—note that the Thai participants were also very familiar with reading Roman script. Thai children begin to learn the letters of the Roman alphabet either in Kindergarten (private school) or Grade 1 (public school). Based on prior research, we can predict that the English native speakers will demonstrate a similar quartic W-shaped identification pattern for the Roman letters, as the Tydgat and Graingers' French participants (i.e., in particular, an advantage for the initial position over the second position). In addition, the response to the symbols and Thai letters should reveal an advantage for the central letter position, and no advantage for the initial letter position—note that Thai letters will be perceived as unfamiliar symbols.

But the critical issue in the present study is the outcome for the Thai participants (Experiment 2). If the pattern of responding in the English experiment is related to a universal process, regardless of the participants' reading experience, then results for Thai letters and English letters should be similar to those found in Roman script (i.e., a W function with an advantage of the initial position), whereas results for symbols will deviate (i.e., an advantage of the middle position, in terms of an inverted V function). Alternatively, based on prior research on Thai, which has shown divergent results, different language- or script-specific patterns may emerge. There are two basic scenarios. On the basis that letter position coding in Thai seems to have a similar level of flexibility of the initial and internal letter positions during reading (Winskel et al., 2012), one possibility is that due to the unspaced nature of Thai script, we can envisage that the elongation of receptive field for the initial letter position, as hypothesized to occur for the Roman script, does not occur in Thai; instead, the receptive fields for initial and internal letter positions can be visualized as being similar in shape and size. This would lead to the prediction that we won't find an initial letter advantage and we could, for example, find a similar response to letters as we do for symbols (i.e., an advantage of the middle position; i.e., an inverted V function). Another possibility is that due to the importance of segmenting this unspaced crowded script into lexical components, using less salient cues than interword spaces, there could be a general heightened attentional response to initial letter position (i.e., a W function with a strong linear component). This would arise as an adaptive mechanism to reading in this extremely crowded nonlinear script without interword spaces, and this would be consistent with the lack of parafoveal-on-foveal effects during sentence reading in Thai (i.e., a marker of serial word-by-word reading rather than parallel reading; Winskel & Perea, 2014). As indicated earlier, in the MRF theory (Tydgat & Grainger, 2009), the advantage of the initial position arises to optimize the very specific nature of letter strings. Tydgat and Grainger hypothesized that a change in size and shape of the receptive fields of retinotopic letters or numbers underlies this adaptive process. This is an adaptive mechanism that has been developed to optimize processing in crowded conditions associated with reading words in the spaced, Roman script, and its role may even be more generalized in Thai—it may be important to note here that keyboard symbols may also be used in conjunction with Thai script similarly to how they are used in Roman script.

2. Experiment 1 (English readers)

2.1. Method

2.1.1. Participants

Thirty-nine individuals took part in the experiment. All of them were English-speaking participants recruited through Southern Cross University, Coffs Harbour, Australia. Participation was voluntary. None of the participants were familiar with Thai script. All participants had normal or corrected to normal vision.

2.1.2. Stimuli and design

The method and procedure used here is based on Tydgat and Grainger (2009). All stimuli consisted of horizontal arrays of five characters, which were either Roman consonant letters presented in uppercase (B, D, F, G, K, N, L, S, and T), Thai consonant letters (ก, ด, น, ล, ษ, ข, ห, ย, and ธ), and symbols (%, /, ?, @, }, <, £, §, and µ). The Roman letters and symbols were displayed in 18-point Courier New font and the Thai letters were displayed in 26-point Courier Thai Proportional font, so that the size of characters was the same. Thai letters can be visually similar, but in the current study visually distinct Thai letters were selected. These three categories were assigned to three blocks: 90 Roman letter-array stimuli, 90 Thai letter-array stimuli, and 90 symbol-array stimuli. The presentation order of the blocks was counterbalanced between participants. The two factors manipulated were (a) target type (Roman letter, Thai letter, or symbol) and (b) target position in the array (Positions 1–5). Each array consisted of a quasi-random sequence of characters, with each of the target characters being presented 2 times at each of the five target positions and 40 times at a non-target position. Thus, accuracy for each type of target at each target position was based on 18 observations per participant. The correct alternative appeared once above the backward mask (with the incorrect alternative below) and once below the backward mask (with the incorrect alternative above) for each target position (refer to Fig. 1).

2.1.3. Procedure

The experiment was controlled with E-Prime software (Psychology Software Tools, www.pstnet.com/eprime). Participants were seated in front of a computer screen at a viewing distance of approximately 60 cm. The instructions were read and explained to the participant by the experimenter, and then the participant had 20 practice trials. Each trial began with two vertical fixation bars, placed above and below the center of a forward mask. The forward mask consisted of five hash marks and stayed on the screen for 515 ms. Subsequently, the array of five characters appeared for a duration of 200 ms. Tydgat and Grainger (2009) presented the stimuli for 100 ms duration, but when trialed with Thai participants, it was found not to be of sufficient duration. Instead, 200 ms duration was used, which corresponds with the duration used by Ziegler et al. (2010) in their study. This was followed by a backward mask, which was identical to the forward mask and was accompanied by two characters, one above the mask and one below at one of the five possible array positions. Participants were required to decide which one of these two characters was present in the corresponding position of the preceding array. They could either press the upward arrow key on the keyboard for the character above or the downward arrow key for the character below the array. Participants were asked to respond as accurately as possible. After a response was made, the screen was cleared, and the two fixation bars reappeared on the screen. After 515 ms, the next trial commenced. Participants could have a break between the three blocks of 90 trials if required. The experiment lasted approximately 20 min.

3. Results and discussion

Mean accuracies for target positions for the English speakers for each target type are presented in Fig. 2. An analysis of variance (ANOVA) was

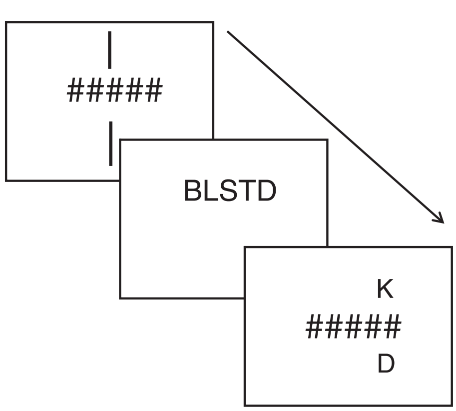

Fig. 1. Illustration of the experimental procedure in Experiments 1 and 2. A mask and fixation bars were followed by a 5-string stimulus (Roman letters, Thai letters, or symbols) presented for 200 ms, which was followed by a mask with two alternative choices.

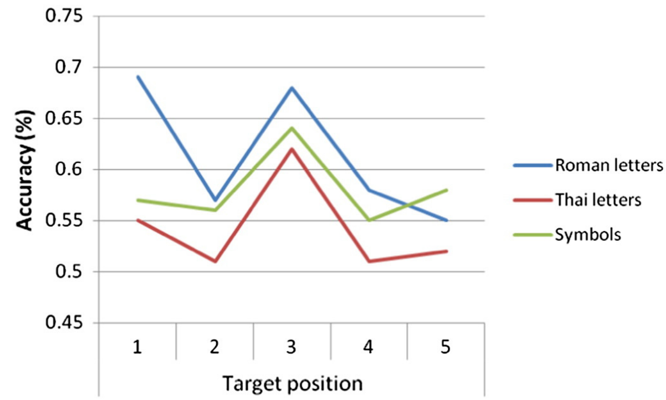

Fig. 2. Mean accuracies for English speakers for each target type and target position.

performed with target type (Roman letter, Thai letter, symbol), target position (1–5) and list (list 1, list 2, list 3) for participants (F_1) and items (F_2). List was included as a factor in the statistical analyses to extract the variability due to the counterbalancing lists. There were significant main effects of target type ($F_1(2,38) = 15.82, p < .001, \eta_p^2 = .31$, $F_2(2,269) = 14.67, p < .001, \eta_p^2 = .04$) and target position ($F_1(4, 38) = 11.19, p < .001, \eta_p^2 = .24, F_2(4,269) = 14.02, p < .001, \eta_p^2 = .07$). Unsurprisingly, accuracy on the unfamiliar Thai letters (54%) was significantly lower than either Roman letters (61%) ($F_1(1,38) = 33.64, p < .001$, ${\eta_p}^2 = .483$, $F_2(1,269) = 27.10$, $p = .001$, ${\eta_p}^2 = .048$) or symbols (58%) ($F_1(1,38) = 9.65, p < .01, {\eta_p}^2 = .211, F_2(1,269) = 7.77, p < .01$, ${\eta_p}^2 = .014$); similarly, accuracy on symbols was significantly lower than English letters ($F_1(1,38) = 6.08$, $p < .05$, ${\eta_p}^2 = .144$, $F_2(1,269) = 5.85, p < .05, {\eta_p}^2 = .011$). There was also a significant interaction effect between target type and target position for participants ($F_1(8,38) = 2.11, p < .05, {\eta_p}^2 = .06$), which approached significance for items ($F_2(2,269) = 1.73, p = .09, {\eta_p}^2 = .02$). Additional analyses for initial position revealed that there was a significant difference for target type ($F_1(2,38) = 14.17$, $p < .001$, $\eta_p^2 = .28$, $F_2(2,269) = 10.15, p < .001, \eta_p^2 = .12$). We further examined the critical initial target position and found that accuracy for English letters was significantly higher than for both symbols ($F_1(2,38) = 16.94, p < .001, {\eta_p}^2 = .320$, $F_2(2,269) = 12.92, p < .001, {\eta_p}^2 = .112$) and Thai letters ($F_1(2,38) = 19.74, p < .001, {\eta_p}^2 = .354, F_2(2,269) = 16.28, p < .001, {\eta_p}^2 = .138$).

As in the study of Tydgat and Grainger (2009), we also performed trend analyses to examine the best fitting serial position functions for the different types of stimuli. Both significant quartic, linear and cubic effects were found for Roman letters, $F_1(1,38) = 25.74$, $p < .001$; $F_2(1,269) = 16.48, p < .001$; $F_1(1,38) = 17.25, p < .001, F_2(1,269) = 17.90, p < .001$; $F_1(1,38) = 7.49, p < .01$; $F_2(1,269) = 5.19, p < .05$, respectively. These effects explained 99% of the observed variance, with 41% due to a quartic function (W shape), 45% due to a linear function, and only 13% due to a cubic function. This is similar to the pattern reported by Tydgat and Grainger (2009; Experiments 1 and 2) and Ziegler et al. (2010). For the symbols, there was also a significant quartic effect (W shape), $F_1(1,38) = 13.11$, $p = .001$; $F_2(1,269) = 10.55$, $p < .001$, which explained 89% of the observed variance, which revealed an advantage of the 3rd letter position over the other letter positions—while the external letter positions were not recognized worse than their adjacent letters (see Fig. 2). Again, this pattern of data was similar to that reported by Tydgat and Grainger (2009) and Ziegler et al. (2010). Finally, for the Thai letters, there was a significant quartic effect (W shape), $F_1(1,38) = 17.39$, $p < .001$; $F_2(1,269) = 15.12$, $p < .001$, which explained 80% of the observed variance, in a way similar to that for the symbols (see Fig. 2).

In summary, we have conducted a comparable study to that of Tydgat and Grainger (2009) with English-speaking participants and have found a similar pattern of results. In Experiment 2, we examined how closely the results with the Thai participants correspond to the English participants' data—that is, Experiment 2 was exactly the same as in Experiment 1 except that the participants were native Thai speakers.

4. Experiment 2 (Thai readers)

4.1. Method

4.1.1. Participants

Thirty-nine Thai native speakers took part in the experiment. They were recruited from Chulalongkorn University, Bangkok, Thailand and tested at the Center for Research in Speech and Language Processing (CRSLP). Participants were paid to participate and were also very familiar with the Roman script. All participants had normal or corrected to normal vision.

4.1.2. Stimuli, design, and procedure

They were the same as in Experiment 1.

5. Results and discussion

Mean accuracies for target positions for the Thais for each target type are presented in Fig. 3. The statistical analyses were the same as in Experiment 1. There was a significant main effect of target position ($F_1(4,38) = 12.92$, $p < .001$, $\eta_p^2 = .26$, $F_2(4,269) = 30.41$, $p < .001$, $\eta_p^2 = .14$). However, unlike the experiment with native speakers of English, there was not a significant difference for target type ($F_1(2,38) = .34$, *ns*, $F_2(2,269) = .27$, *ns*) and there were no trends of an interaction effect of target type by target position ($F_1(8,38) = 1.15$, *ns*, $F_2(8,269) = .95$, *ns*). We further examined the critical initial target position and found no significant difference for target type ($F_1(2,38) = 1.87$, *ns*, $F_2(2,269) = 1.37$, *ns*).

We also performed trend analyses to examine the best fitting serial position functions for the different types of stimuli. Both significant quartic (W shape) and linear effects were found for Roman letters, $F_1(1,38) = 9.16$, $p < .01$; $F_2(1,269) = 8.49$, $p < .001$, and $F_1(1,38) = 18.82$, $p < .001$; $F_2(1,269) = 51.49$, $p < .001$, respectively. These effects explained 95% of the observed variance, with 82% due to a linear function and only 13% due to a quartic function (W shape). For the symbols, there was also a significant linear effect, $F_1(1,38) = 12.12$, $p = .001$; $F_2(1,269) = 19.88$, $p < .001$ and marginal quartic effect, $F_1(1,38) = 3.05$, $p = .09$, which explained 91% of the observed variance, with 77% due to linear effects and 14% due to a quartic function. Finally, for the Thai letters, there was a significant linear effect, $F_1(1,38) = 26.37$, $p < .001$, $F_2(1,269) = 34.87$, $p < .001$, marginal quadratic effect, $F_1(1,38) = 3.54$, $p = .07$, $F_2(1,269) = 6.05$, $p < .05$ and quartic effect, $F_1(1,38) = 3.31$, $p = .08$, $F_2(1,269) = 2.77$, $p = .10$, which explained 98% of the observed variance, with 78% due to linear effects, 14% due to quadratic effects and 6% due to quartic effects.

In summary, the pattern exhibited by the Thais for Thai letters, Roman letters, and symbols was remarkably similar: the function described mainly a linear effect whereas the quartic effect was substantially less prevalent than with the English-speaking participants. Interestingly, in contrast to the English-speaking participants, the pattern for symbols was similar to that for Thai letters and Roman letters.

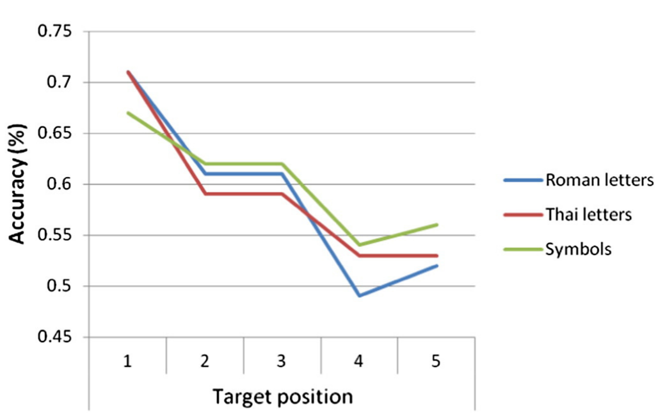

Fig. 3. Mean accuracies for Thais for each target type and target position.

6. Joint analyses of Experiments 1 and 2 (English vs. Thai readers)

To examine the similarities/differences across experiments, we conducted a combined analysis of English and Thai data (Experiments 1–2). Mean accuracies for target positions in the two language groups for Roman letters and symbols are presented in Fig. 4. Roman letters and symbols were included but not Thai letters, as they have the added confound that they are letters for the Thais but are perceived as unfamiliar symbols by the English speakers. The analysis of variance (ANOVA) was parallel to those reported earlier, except that language group (Thai, English) was now included as a factor in the design. There was not a significant main effect of language group ($F_1(1,77) = .02$, *ns*, $F_2(1,179) = .04$, *ns*) or target type ($F_1(1,77) = 2.03$, *ns*, $F_2(1,179) = 1.72$, *ns*), but there was a significant main effect of target position ($F_1(4,77) = 16.06$, $p < .001$, $\eta_p^2 = .18$, $F_2(4,179) = 24.32$, $p < .001$, $\eta_p^2 = .09$). In addition, there was a significant interaction effect of language group by target type ($F_1(1,77) = 6.40$, $p < .05$, $\eta_p^2 = .08$, $F_2(1,179) = 5.39$, $p < .05$, $\eta_p^2 = .01$), language group by target position ($F_1(4,77) = 3.45$, $p < .01$, $\eta_p^2 = .05$, $F_2(4,179) = 5.23$, $p < .001$, $\eta_p^2 = .02$) and target type by target position ($F_1(4,77) = 4.69$, $p < .01$, $\eta_p^2 = .06$, $F_2(4,179) = 3.80$, $p < .01$, $\eta_p^2 = .02$). The significant language group by target type interaction effect was due to the higher accuracy of the English participants on the Roman letters (61%) than the symbols (58%), $F_1(1,38) =$

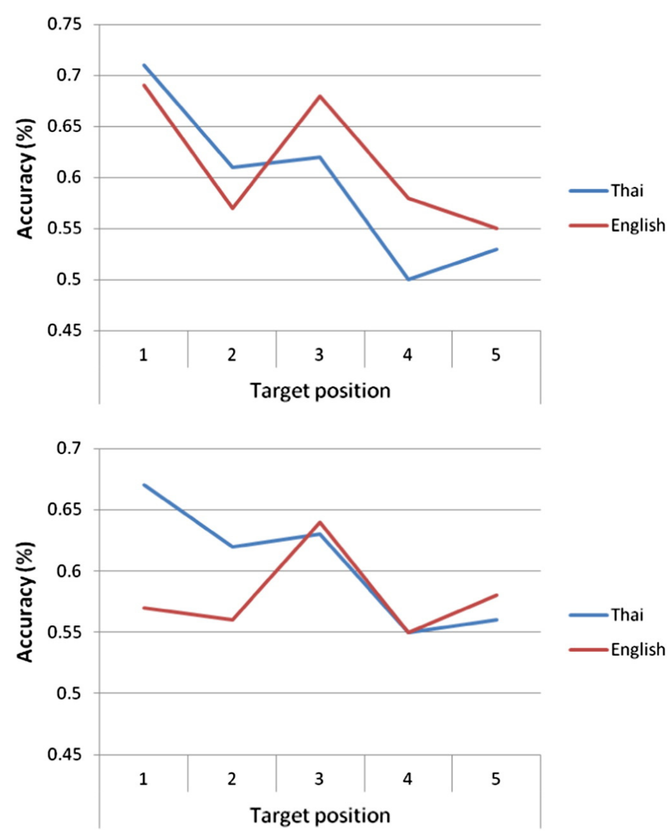

Fig. 4. Mean accuracies for target positions in the two language groups for Roman letters and symbols: Roman letters (top), symbols (bottom).

6.08, $p = .05$, $\eta_p^2 = .144$, $F_2(1,179) = 3.87$, $p < .05$, $\eta_p^2 = .01$, whereas there was no significant difference between Roman letters (59%) and symbols (60%) for the Thais (Fs < 1). Further analyses revealed that, for the initial target position, there was a significant language group by target position interaction for participants ($F_1(1,77) = 4.02$, $p < .05$, $\eta_p^2 = .05$), which approached significance for items ($F_2(1,179) = 2.84$, $p = .09$, $\eta_p^2 = .01$). This was due to the Thais being more accurate on the symbols than the English speakers, $F_1(1,77) = 8.61$, $p < .01$, $\eta_p^2 = .107$, $F_2(1,179) = 8.85$, $p < .01$, $\eta_p^2 = .080$, whereas there was no significant difference between the Thai and English speakers for Roman letters (Fs < 1). Moreover, the English participants were more accurate on the Roman letters than the symbols, $F_1(1,38) = 16.94$, $p < .001$, $\eta_p^2 = .320$, $F_2(1,179) = 12.92$, $p < .001$, $\eta_p^2 = .112$, but there was no significant difference for the Thais (Fs < 3).

In summary, the results highlight the difference in response to the symbols by the English and Thai participants, with Thais responding similarly to the symbols as they do to the Roman letters. The Thais exhibit higher accuracy for initial symbols than the English speakers. It appears that Thais have an enhanced perception of the initial position of strings (regardless of the type of stimuli—letters or symbols) in comparison to the English participants. This heightened perception for symbols may be due to Thais' experience of reading Thai with its distinctive visually complex and crowded nonlinear script without interword spaces.

7. General discussion

In the current study, we carried out a comparable 2AFC experiment as conducted by Tydgat and Grainger (2009) to measure identification accuracy for all positions in a string of five characters consisting of Roman letters, Thai letters or symbols in both English- and Thai-speaking participants. It is essential to conduct research on diverse languages and scripts if we are to delineate between universal and script-specific effects (see Ktori & Pitchford, 2008). For the English participants (Experiment 1), we found a similar pattern of results to those of Tydgat and Grainger (2009), namely an initial letter advantage for Roman letters (a W function) but not for Thai letters or symbols (an inverted V function). For the Thai participants (Experiment 2), who are familiar with reading both Roman and Thai script, we found an advantage of the initial position which was remarkably similar for Thai letters, Roman letters, and symbols. Taken together, these results illustrate a striking difference in response to the symbols by the English and Thai participants with Thais responding to the symbols as they do to the Roman letters and Thai letters. In particular, the Thais exhibited higher accuracy for initial symbols than the English participants.

In relation to the predictions made in the Introduction, we found qualified support for the MRF theory (Tydgat & Grainger, 2009), in that we found an advantage of initial position in Thai, but this effect was not reserved for letters only but also applied to the symbols. It may be important to note here that in the experiments of Tydgat & Grainger (2009; see also Ziegler et al., 2010), the advantage of the initial position occurred not only for strings of letters, but also for strings of digits. Tydgat and Grainger claimed that the changes in size of the receptive fields would affect those stimuli that "normally appear in strings", such as letters and digits—this reasoning would exclude symbols (see Grainger & Dufau, 2012). In the present experiments, we found support for a language- or script-specific perspective too, which we propose is due to an adaptive specialized process occurring when reading this visually complex and crowded nonlinear script without interword spaces (and which may include symbols). In Thai, with experience of reading, smaller receptive field sizes may develop as reading skills become more honed in this extremely crowded letter environment. It also appears that this mechanism applies to symbols as well as letters, which is consistent with the fact that symbols may occur in the same dense conditions as Thai letters—had we included strings of digits, the results with Thai readers would most likely have been similar to the strings of letters and symbols (i.e., a serial function with an advantage for the initial position). We must keep in mind that, unlike letters, digits do not activate the "visual-word form area" to a greater level than symbols (see Baker et al., 2007). Therefore, the letter/digit vs. symbol dissociation reported by Tydgat and Grainger (2009) cannot have its origin in that brain area; instead it should occur in earlier low-level processing areas—these areas are common for letters/digits (but not for symbols) for English readers, whereas they appear to be common for letters/symbols (and presumably digits) for Thai readers.

However, the special role found in the initial position for both letters and even symbols in Thai may seem at odds with previous results found when reading continuous Thai sentences with words with initial and internal transposed letters and interword spaces and demarcation of word boundaries manipulated (Winskel et al., 2012). In that experiment, there was no apparent difference in the degree of disruption caused by initial and internal transpositions, whereas in English a reading cost was found for reading words with initial in comparison to internal transpositions (White et al., 2008). Of particular relevance here is that we did not find the magnitude of the transposed letter effect to be modulated by the spacing manipulation. In other words, we did not find shorter reading times in the spaced than unspaced condition with initial transpositions than internal transpositions, where theoretically there would be less lateral masking on initial letters. How can we explain this apparent incongruity in results of the previous and current studies on Thai? In the study of Winskel et al. (2012), participants were reading words in sentences, whereas in the current study participants identified letters and symbols in character strings that were displayed for very short durations. Thus, different stages or levels of processing may be reflected in the two tasks; a lower earlier level of processing is involved in letter identification, whereas a later higher level of processing is involved in word identification and reading. We can envisage that at the early stages of letter or symbol identification that initial letter position is preferentially attended to. This is also important for parafoveal word segmentation when reading in a script without salient interword spaces (see Winskel & Perea, 2014). It appears that skilled Thai readers use language- or script-specific word segmentation patterns or cues for this purpose (Winskel, Radach, & Luksaneeyanawin, 2009). Whereas in later lexical processing, attention is focused on both initial and internal letter positions to effectively decode the syllable and word. Thai has nonlinear characteristics in that vowels can occur above or below the main text line or either side of the consonant, and importantly, vowel letters and tone diacritics combine and operate at the syllable or word level (see Winskel, 2014, for more detail about Thai script). Both these processes appear to be adaptive strategies that are shaped by the distinctive characteristics of the Thai script.

In summary, consistent with the modified receptive field (MRF) theory (Tydgat & Grainger, 2009), we found evidence that the size of the receptive field of letters becomes smaller in skilled readers in Thai script. Importantly, unlike the Roman script, in Thai this has been generalized beyond letters (i.e., to symbols) presumably due to the dense conditions of Thai reading. In future studies, it would be worthwhile examining if the patterns found in Thai also occur for other types of symbols and from a developmental perspective as well as to examine to what degree letter processing differs from symbol processing in Thai (e.g., via the similarities/differences in the magnitude of transposition effects with letters vs. symbols). It would also be intriguing to investigate if similar script-specific patterns or processes also apply to other scripts without interword spaces (e.g., Chinese, Japanese, Burmese or Khmer).

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