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Eye movements while reading an unspaced writing system: The case of Thai

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ABSTRACT

Thai has an alphabetic script with a distinctive feature – it has no spaces between words. Since previous research with spaced alphabetic systems (e.g., English) has suggested that readers use spaces to guide eye movements, it is of interest to investigate what physical factors might guide Thai readers' eye movements. Here the effects of word-initial and word-final position-specific character frequency, word-boundary bigram frequency, and overall word frequency on 30 Thai adults' eye movements when reading unspaced and spaced text was investigated. Linear mixed-effects model analyses of viewing time measures (first fixation duration, single fixation duration, and gaze duration) and of landing sites were conducted. Thai readers tended to land their first fixation at or near the centre of words, just as readers of spaced texts do. A critical determinant of this was word boundary characters: higher position-specific frequency of initial and of final characters significantly facilitated landing sites closer to the word centre while word-boundary bigram frequency appeared to behave as a proxy for initial and final position-specific character frequency. It appears, therefore, that Thai readers make use of the position-specific frequencies of word boundary characters in targeting words and directing eye movements to an optimal landing site.

1. Introduction

Many languages of the world have writing systems that use spaces to delimit words, a feature that facilitates the targeting by the eyes of the optimum location for word recognition, near its centre (O'Regan & Jacobs, 1992; Rayner, 1979). There have, however, been few systematic studies of reading *scriptio continua* languages (those written without spaces between words) to ascertain whether spaces between words are a *necessary* condition for these optimum fixations.

1.1. Eye movements in spaced and scriptio continua languages

Most research on eye movements in reading has investigated European languages, using spaced writing systems. It has been debated whether spaces between words are a necessary condition for directing eye movements to the optimal position in the word for reading, or whether they simply facilitate reading in some less specific manner. Accordingly, many studies have manipulated spacing in European alphabetic writing and the reading rate of people accustomed to spaces between words slows by approximately 35% when spaces are removed from the text (Inhoff et al., 1989; Pollatsek & Rayner, 1982; Rayner, 1998; Rayner, Fischer, & Pollatsek, 1998; Rayner & Pollatsek, 1996; Spragins, Lefton, & Fisher, 1976).

The typical landing site on a word in spaced English, referred to by Rayner (1979) as the preferred viewing location (PVL), is about halfway between the word centre and word beginning. A complementary notion is that of optimal viewing position (OVP; O'Regan & Jacobs, 1992), which is the location at which the word is most readily recognised. The OVP is nearer to the word centre though still slightly to its left. The PVL of readers of English shifts towards the beginning of the word when reading unspaced text (Rayner, 1998; Rayner & Pollatsek, 1996), which suggests that readers of English and spaced writing systems in general use different oculomotor strategies when reading spaced and unspaced texts. These studies show that while the absence of spaces for readers of normally spaced text does not make reading impossible, it shifts the PVL towards the presumably less efficient word-initial position. Indeed, the results show that in addition to the shift of the PVL towards the word beginning, unspaced English text also results in longer fixation durations (Rayner, Fischer, & Pollatsek, 1998). These results suggest that spaces between words are an important visual cue for readers, but not a necessary condition for reading to proceed.

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On the basis of the shift in PVL by readers of normally spaced text reading unspaced text, it might be expected that readers of *scriptio continua* languages would also show PVLs near the beginning of words. Based on the same reasoning, it is also possible that if spaces between words were available for *scriptio continua* readers, they might perform better, as indexed by shorter viewing times and a shift in PVL from word beginning towards word centre.

Japanese script is a hybrid ideographic/syllabic writing system without spaces between the words. Nevertheless Japanese offers other visuo-lexical cues to word boundaries. Modern Japanese is written in a mixture of three character types: Kanji, a morphographic character set, and two syllabaries, Hiragana and Katakana. Kanji characters are visually more complex than Katakana or Hiragana and their location appears to serve as a visual cue for fixations (Kajii, Nazir, & Osaka, 2001). Kajii, Nazir, and Osaka (2001) studied eye movement control in reading Japanese and showed that Japanese readers' PVL was indeed located at the first character of the word, analogous to English readers reading unspaced English text (Rayner, Fischer, & Pollatsek, 1998). In addition, the average fixation duration for Japanese readers reading normal unspaced Japanese text was 275 ms (ms) (Kajii, Nazir, & Osaka, 2001), which is shorter than English readers reading unspaced English text (378 ms), but a little longer than English readers reading spaced text (253 ms; Rayner, Fischer, & Pollatsek, 1998).

Moving to the manipulation of spaces in Japanese, Sainio et al. (2007) recorded eye movements of native Japanese readers reading either Hiragana (syllabic) or mixed Kanji–Hiragana (ideographic–syllabic) texts in spaced or unspaced conditions. Spaces between words facilitated word identification and eye guidance when the readers read Hiragana script, but not the mixed Kanji–Hiragana text. The readers' PVL shifted to the word centre when reading spaced Hiragana, but remained at the word beginning for spaced Kanji–Hiragana texts. Presumably the Kanji characters serve as effective segmentation cues in Kanji–Hiragana text so that the additional space information is redundant for segmenting words (Sainio et al., 2007).

The effect of spaces between words has also been investigated in Chinese. Bai et al. (2008) presented Chinese ideographic text in four conditions: unspaced (the norm), appropriate spaces at word boundaries, appropriate spaces between each character, and inappropriate spaces between characters resulting in apparent non-words. The main objectives of this study were to find out if spaces facilitate reading and whether the word or character was the primary target during reading in Chinese. The results indicated that sentences with unfamiliar word-spaced format were as easy to read as the visually familiar unspaced text. However, spacing that created non-words and spaces between characters produced longer reading times.

With respect to the primary unit, overall reading times from Bai et al. (2008) indicated that the word rather than the character was the primary unit of information for the Chinese reader. In addition, Yan et al. (2006) found a complex interplay between the effects of initial character frequency and word frequency on viewing times, with overall word frequency modulating the effects of character frequency. Yan et al. (2010) studied saccade targeting of Chinese readers – whether they aimed to land their first fixation at word centre or word beginning. Analysing landing site location on words with different word length they found that Chinese readers tended to land their eyes at the word centre in single-fixation cases and at word beginning in multiple-fixation ones and concluded that Chinese readers dynamically targeted word centre if the segmentation of parafoveal word boundaries was successful and word beginning if segmentation failed. A recent study by Li, Liu, and Rayner (2011) investigating landing site distributions in reading normal Chinese text confirmed the Yan et al. (2010) finding. Li, Liu, and Rayner (2011) showed that Chinese readers tend to show a combination of word-based and character-based targeting, depending on word-segmentation processes. Taken together, the picture from Chinese reading studies suggests readers adopt a dynamic and adaptive reading strategy.

1.2. Thai language

Thai is a tonal monosyllabic, mono-morphemic language consisting of words with an average length of about three to four syllables, but comprising many compound words. It uses an alphabetic *scriptio continua* writing system, written from left to right in horizontal lines starting from the top of the page. All consonant and some vowel characters are written horizontally in the main line. However, some specific vowel characters, which we will refer to as upper and lower vowels, are written vertically above or below the initial consonant character (the second of a pair in the case of consonant clusters). All tone characters are placed above the initial consonant character (on top of an upper vowel, if also present) and some diacritics and special symbols are placed above the final consonant character. As a result, Thai is considered to have a complex orthography, though with a high degree of grapheme-to-phoneme correspondence. While Thai is written without spaces between words, spaces are used as a form of punctuation to indicate the ends of phrases, clauses or sentences. Moreover, initial reading instruction is conducted with spaced texts in Kindergarten and First Grade, before children move onto unspaced text in Second Grade. Word segmentation in Thai depends very strongly on sentential context, since many Thai character strings can have several readings. For example, "ตากลม" can be read as [tà:k lōm] ("exposed to wind") or [tā: klōm] ("round eyes"). To give a feel for Thai text, two example sentences are presented in Table 1.

Kohsom and Gobet (1997) investigated the effects of adding spaces to Thai text. They employed a 2 × 2 design, crossing text coherence with the presence or absence of word spacing. Thai and English texts were rendered incoherent by scrambling the word order. Participants were given a cue before each paragraph was presented on the screen to show whether the next paragraph would be spaced or unspaced. Participants' oral reading was recorded and their reading speed and errors were measured. The results showed that Thai readers read the coherent text significantly faster than incoherent text, and that reading the spaced variant was always faster than the unspaced one. The results also showed that the participants made less reading errors when reading spaced texts. Thai readers, although familiar with reading text without spaces, appeared able to use spaces to improve their reading rate and accuracy. Spaces, therefore, seem to function as a robust cue to word boundaries across alphabetic languages (Kohsom & Gobet, 1997). However, this study examined only the effects of spaces on reading rate and accuracy and did not provide any information on the eye movement behaviour of Thai readers. So it is unclear whether Thai readers use different oculomotor strategies to those of readers of spaced text, as appears to be the case for Japanese readers (Sainio et al., 2007).

The first study of eye movements in reading Thai was conducted by Reilly et al. (2005). They investigated eye movements in Thai readers reading normal, unspaced Thai text and

Table 1
Examples of Thai sentences (the sequences [tà:klōm] vs. [tā:klōm] are underlined in the two sentences).

นิดมีกระต่ายตัวเล็กตากลมตัวหนึ่งชื่อปุกปุย
[Nid has one small round-eyed rabbit named Pukpui.]
เก้าอี้ถูกทิ้งตากแดดตากลมอยู่สนามหลังบ้าน
[The chair was left exposed to the sun and wind in the backyard.]

Table 2
Eye movements in reading with and without spaces between words.

	Spaced writing system	Scriptio continua writing system	
	Alphabetic [English] (Rayner, Fischer, & Pollatsek, 1998)	Ideographic [Japanese and Chinese] (Bai et al., 2008; Kajii, Nazir, & Osaka, 2001; Sainio et al., 2007)	Alphabetic (Thai) (Reilly et al., 2005; Winskel et al., 2009)
Fixation duration	~253 ms (*normal texts*)	~250 ms (*normal texts*)	~204 ms (*normal texts*)
	~378 ms (*unspaced texts*)	~231 ms (*spaced texts*)	~206 ms (*spaced texts*)
Landing site	Word centre (*normal texts*)	Word beginning (*normal texts*)	Word centre (*normal texts*)
	Word beginning (*unspaced texts*)	Word beginning (*spaced texts*) Word centre (*Hiragana spaced text*)	Word centre (*spaced texts*)

surprisingly found that the PVL of Thai readers reading unspaced text was near the centre of the word, similar to the PVL of European spaced text readers. What could be the visual cue(s) that Thai readers use to achieve this similar PVL? Reilly et al. (2005) proposed that the word-initial and word-final position-specific frequency of consonants could well be important in reading Thai and included these frequencies in their analysis. They found that the PVL was closer to the word centre if the fixated word ended with a high rather than a low position-specific frequency character.

Since Reilly et al. only investigated eye movements in reading normal, unspaced text, it was not possible to determine whether spaces between words had any effect on eye movement patterns and eye movement control of Thai readers. If the Reilly et al. (2005) finding regarding the PVL of Thai readers is robust and Thai readers' PVL is near the word centre, then spaces between words should not have a significant effect on their eye movements. While spaces may facilitate Thai reading accuracy, they should not play as important a role in guiding eye movements as they do in spaced writing systems readers. This facilitative but non-critical role of spacing is supported by the results of Winskel, Radach, and Luksaneeyanawin (2009), who investigated eye movements of bilingual Thai–English readers when reading spaced and unspaced Thai and English. They found that spaces between words facilitated word recognition but did not affect eye guidance or lexical segmentation. Initial landing positions were similar in spaced and unspaced texts, just left of the word centre.

A summary of the studies investigating fixation durations and landing sites in different writing systems with spaced and unspaced text is provided in Table 2. In general, readers' PVL for spaced text is normally at or near the word centre whereas for unspaced text it is at the beginning of the word. However, the results of research on Thai do not accord with this general trend; despite the fact that Thai readers read spaced texts more quickly than unspaced texts, Thai readers' PVL for both normal unspaced and spaced text is near the centre of the word (Reilly et al., 2005; Winskel, Radach, & Luksaneeyanawin, 2009). The primary aim of this study is, therefore, to determine the critical features of Thai script that might facilitate targeting of the word centre in the absence of visually salient word boundaries.

1.3. Motivation for the present study

There have been several studies of spaced writing systems involving a number of languages (e.g., Finnish, German, and English) that suggest that the saccade amplitude of readers is sensitive to a target word's orthographic regularity (Hyönä & Pollatsek, 1998; Radach, Inhoff, & Heller, 2004). Radach, Inhoff, and Heller (2004) studied the effect of the frequency of initial four-letter clusters (quadrigrams) on incoming saccade amplitudes. They examined compound and non-compound words in an effort to determine the locus of the effect; whether it was orthographic or lexical. They found that words comprising higher-frequency initial quadrigrams attracted landings further into the body of the word. The pattern of their results suggested that the source of the amplitude modulation was indeed orthographic.

Previous research has shown that the saccade amplitude of Thai readers appears to be sensitive to the presence of a small set of characters that tend to be diagnostic of word boundaries (Reilly et al., 2005). When these characters are present at word boundaries (beginning and end), saccades tend to land nearer the word centre. Table 3 lists the set of characters that occur most frequently in either first or last word positions. In the case of the word-initial position, 10 characters account for just over 50% of all initial character occurrences, while five characters account for roughly the same percentage in the last position. However, in light of the Radach, Inhoff, and Heller (2004) findings, there may be a confound between single character frequency and boundary bigram frequency. So rather than being a first-order orthographic effect involving single characters at word boundaries, it may be a second-order effect involving boundary bigram frequencies. By boundary bigrams we refer to the pairs of characters comprising the final character of word $N-1$ and the initial character of word N as well as the final character of word N and the initial character of word $N+1$. Of course, boundary bigrams have a dual nature. For example, the $N-1/N$ bigram is both the initial bigram for word N and the final bigram for word $N-1$. Nonetheless, since the focus of our analyses will always be on word N, any reference to boundary bigrams from here on will refer to word N-initial and word N-final bigrams. Note, that we would expect word-boundary bigram frequencies to operate in the opposite manner to single character frequency: the presence of a low-frequency bigram would indicate a word boundary, whereas according to the Reilly et al. (2005) hypothesis, a high position-specific frequency initial and/or final character would play the same role.

Table 3
Frequency of occurrence of word-boundary characters in Thai.

	IPA	%	Cum. %
First character			
เ	/eː/	10.9	10.90
น	/n/	8.1	19.00
ท	/tʰ/	6.7	25.70
แ	/ɛː/	6.3	32.00
ไ	/ai/	6	38.00
ก	/k/	4.9	42.90
ค	/kʰ/	4.7	47.60
จ	/tɕ/	4.7	52.30
Last character			
ง	/ŋ/	17.80	17.80
น	/n/	14.00	31.80
ำ	/am/	7.70	39.50
ก	/k/	7.20	46.70
ม	/m/	5.70	52.40

Table 4
Examples of experimental sentences.

Unspaced: หญิงต้องเบียนตัวเลบเพือใช้เป็นโจทย์
Spaced: นักเรียน ใหม่ ชือ ชโลทร มาจาก ต่างจังหวัด

The main hypotheses for this study, therefore, are that (1) the word centre should be the effective target for the eyes during saccadic execution in Thai; (2) characters occurring with higher position-specific frequency at word boundaries should direct the eyes to the word centre more effectively than those with lower position-specific frequencies; (3) low-frequency word-boundary bigrams should provide similar guidance; and (4) spacing should speed recognition of words but not affect word targeting. Note that for the sake of succinctness, from here on, references to word-initial and word-final character frequencies will implicitly refer to position-specific rather than absolute character frequencies.

2. Method

2.1. Participants

Thirty participants, all native Thai-speaking adults and all current students or staff at Chulalongkorn University, Bangkok were paid to participate in this study. Their mean age was 22.8 years, with a range of 18–36 years. Although many of the participants would have had some exposure to English in their academic studies, they could not be said to be bilingual. Moreover, since the focus of the study described here is on low-level aspects of the reading process, it is unlikely that late exposure to English would have had a significant impact on what are highly automated perceptual-motor processes.

2.2. Materials

The stimuli comprised 54 experimental and 20 familiarisation sentences. The average length of the stimulus sentences was 8.6 words (SD = 1.7) or 34 letters (SD = 3.8), and average word-length was 4.74 characters (range: 1–10, SD = 2). Examples of stimuli are given in Table 4.

2.3. Apparatus

Participants' eye movements were recorded with an SR Research Ltd. (www.SR-research.com) EyeLink II eye tracker with a sampling rate of 500 Hz that monitored the position of the participants' left or right eye (depending on which eye was more easily tracked in the initial calibration phase). Participants viewed the stimuli on a 21″ NEC CRT monitor with 1024 × 768 pixel resolution and a 60 Hz refresh rate at a viewing distance of approximately 50 cm. This gave a resolution of approximately 21 pixels per degree of visual arc or just over 1.3 average Thai characters per degree given the font used.

2.4. Procedure

The stimuli were presented in the centre of the computer screen in 22 point Cordia New font, one sentence at a time with a maximum display time of 30 s. However, readers could terminate the reading of a sentence and move onto a new one by pressing a button. Each trial started with a calibration dot located just to the left of the start of the sentence, which participants had to fixate in order to trigger display of the next stimulus. To maintain attention, there was a comprehension question for participants to answer after every experimental sentence.

Each participant was tested individually in a room with minimal noise and light interference at the Centre for Research in Speech and Language Processing (CRSLP), Chulalongkorn University, Bangkok, Thailand. The 20 familiarisation trials were presented in two blocks of nine sentences: one block of spaced text, and another of unspaced text. These were then followed by two familiarisation sentences (one spaced, one unspaced) acting as warm-up trials before the start of the experimental session. The large number of familiarisation trials was to allow readers to become accustomed to reading spaced text, which would be an unusual experience for most Thai readers.

The 54 experimental sentences presented in 3 blocks of 18 (9 spaced and 9 unspaced sentences).

Table 5
Model analyses – significant effects.

Model	Term	β	SE	t	p_{MCMC}	Pr(>|t|)
Landing site	Intercept	−1.319	0.947	−1.392	0.142	0.164
	Log first character freq.	2.595	1.117	2.323	0.015	0.020
	Spacing × log first character freq.	−2.640	1.287	−2.052	0.042	0.040
	Spacing × log word freq.	1.647	0.564	2.921	0.003	0.004
	Spacing × log first character freq. × log last character freq.	3.677	1.643	2.238	0.017	0.025
	Spacing × log first character freq. × log final bigram freq.	−1.582	0.728	−2.174	0.024	0.030
	Spacing × log first character freq. × log word freq.	−1.692	0.802	−2.109	0.030	0.035
	Spacing × log initial bigram freq. × log word freq.	1.663	0.370	4.498	0.0001	0.000
	Spacing × log final bigram freq. × log word freq.	0.872	0.316	2.761	0.005	0.006
	Log last character freq. × log final bigram freq. × log word freq.	0.547	0.252	2.171	0.025	0.030
	Log initial bigram freq. × log final bigram freq. × log word freq.	−0.231	0.121	−1.917	0.059	0.055
First fixation duration	Intercept	224	6.157	36.300	0.0001	0.000
	Spacing × log last character freq. × log initial bigram freq.	10.838	4.937	2.200	0.028	0.028
Single fixation duration	Intercept	227	7.040	32.460	0.0001	0.000
	Log first character freq. × log last character freq.	−23.662	9.893	−2.390	0.013	0.017
	Log initial bigram freq. × log word freq.	4.793	2.385	2.010	0.036	0.045
	Log first character freq. × log last character freq. × log final bigram freq.	−7.488	4.077	−1.840	0.038	0.066
Gaze duration	Intercept	242	8.143	29.744	0.0001	0.000
	Log first character freq.	16.933	8.847	1.914	0.046	0.056
	Log word freq.	−18.559	3.940	−4.711	0.0001	0.000
	Spacing × log last character freq. × log word freq.	15.417	5.414	2.848	0.004	0.004

Note: Freq. stands for frequency.

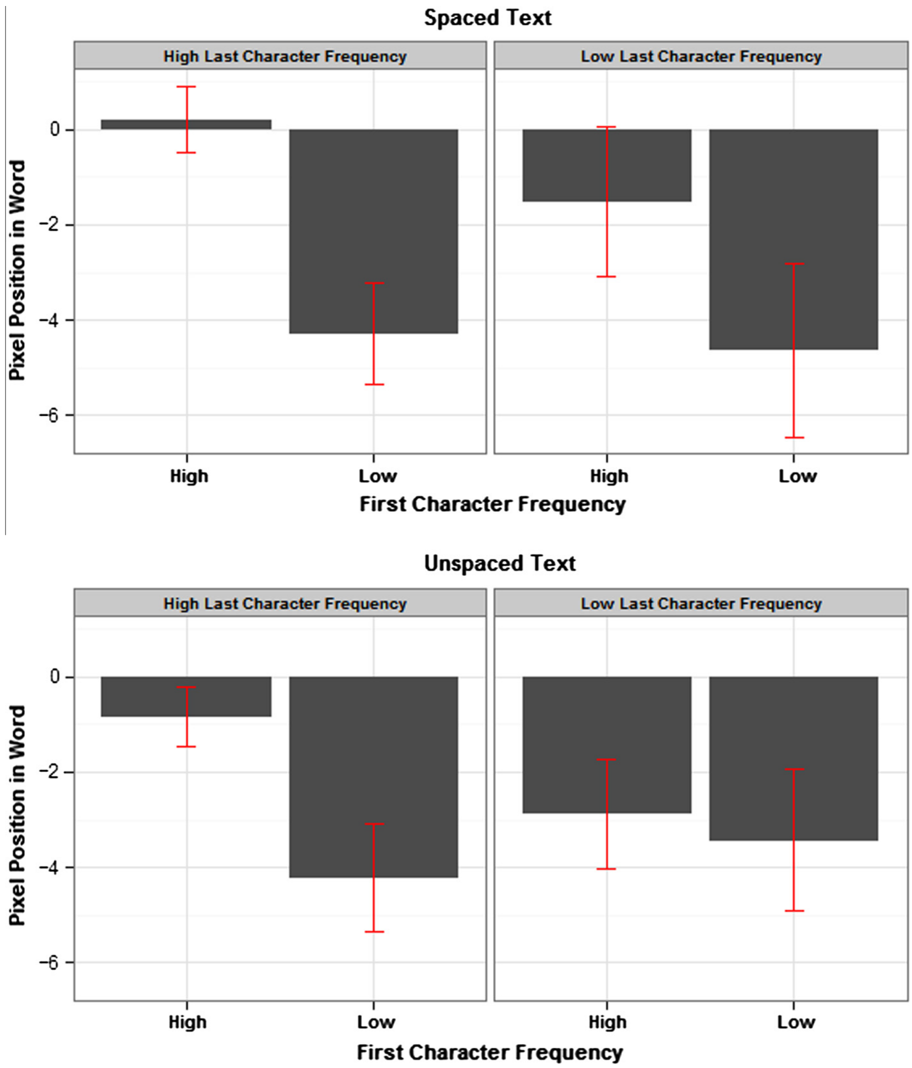

Fig. 1. Landing site variation as function of initial and final position-specific character frequency and inter-word spacing. The landing site position is measured in pixels and is relative to the word centre. Negative numbers indicate landings closer to the word beginning. Character frequency is dichotomised around the mean.

2.5. Data analysis

A number of standard data filtering measures were used. Fixation durations shorter than 60 milliseconds (ms) and greater than 800 ms were excluded from all analyses. The overall exclusion rate at this point was approximately 1%. In addition to outlier exclusion, fixations on the first and last words of each line were also omitted from analysis. Further, each of the viewing time measures limited the number of valid observations included in the analyses. The total number of observations involved in the various analyses described below was, therefore, as follows: landing site and first fixation duration (7347), single fixation duration (4216), and gaze duration (5372).

Eye movement data were analysed in terms of landing sites on words, first fixation duration, single fixation duration, and gaze duration, each with an identical linear mixed-effect model (Baayen, Davidson, & Bates, 2008). The linear model used for all analyses comprised a single fixed-effect of spacing (coded as an absent–present contrast) and the position-specific log frequencies of word-initial and word-final characters, word-boundary bigram log frequencies, and word log frequency, each calculated from the 10 million-word CRSLP Thai Language Corpus (Aroonmanakun, Tansiri, & Nittayanuparp, 2009). The random variables included in the model were participant, sentence, and word.

The model thus comprised the following terms:

(1) intercept representing the overall mean of the dependent measure in question;
(2) contrast term for the presence of spacing (absent–present);
(3) covariate for word-initial character log frequency;
(4) covariate for word-final character log frequency;
(5) covariate for word-*N*-initial bigram log frequency;
(6) covariate for word-*N*-final bigram log frequency;
(7) covariate for word log frequency;

all two- and three-way interactions between terms (2) through (7). Note that covariates (3) through (7) were entered in the model as continuous values and centred to give them a mean of zero. This has the benefit of making effect sizes interpretable as deviations from the overall mean represented by the model's intercept.

3. Results

The results of the comprehension questions following the presentation of the stimulus sentences showed that the overall comprehension rate for the 54 test sentences was 94%, indicating that participants had read and understood the vast majority of

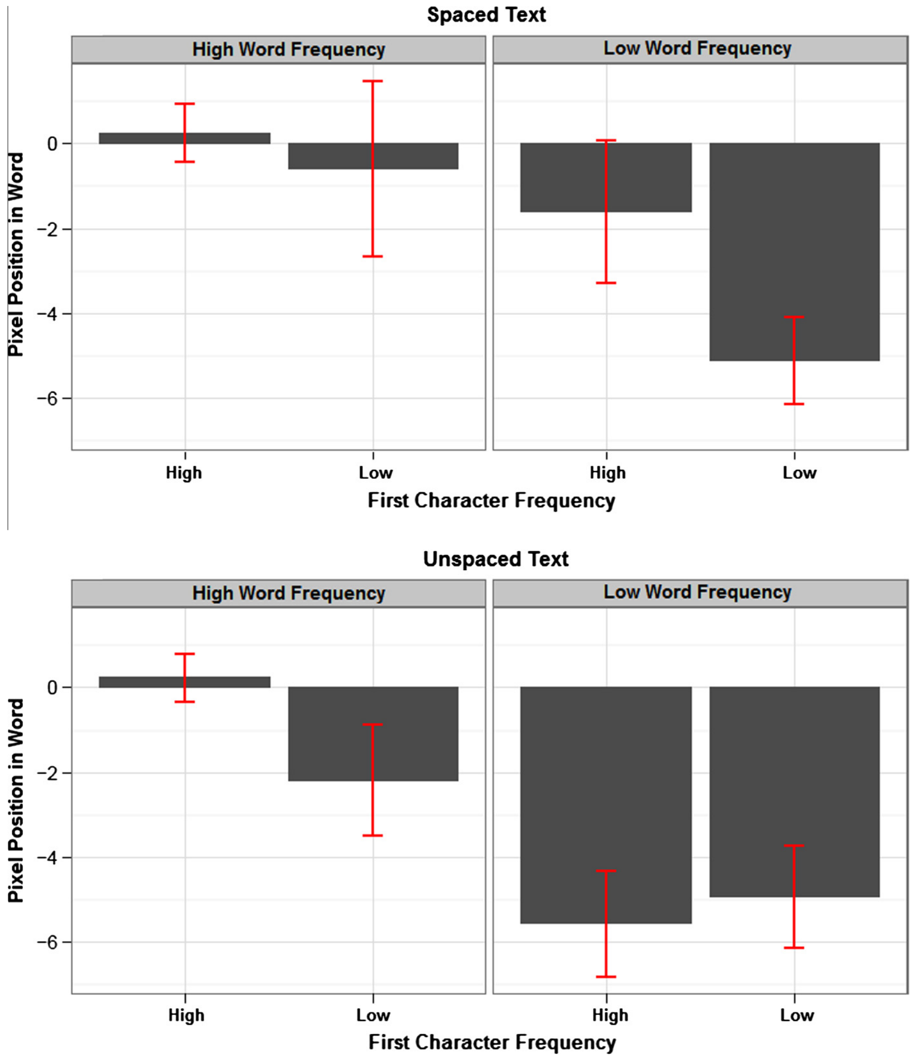

Fig. 2. Landing site variation as a function of initial position-specific character frequency, overall word frequency, and spacing. The landing site position is measured in pixels and is relative to the word centre. Negative numbers indicate landings closer to the word beginning. Character frequency is dichotomised around the mean.

sentences. The model fits for each of the four dependent variables are summarised in Table 5, and detailed analyses of these models are presented below. Note that in the accompanying figures the various frequency-based covariates have been dichotomised around their respective means for the purpose of graphical representation. However, continuous values of these covariates were used in the analyses.

3.1. Landing site analysis

Because Thai fonts are proportional rather than fixed width, we used a landing site measure based on pixel position rather than character position. As a guide, the average width of a Thai character in our study was approximately 16 pixels and a space was 12 pixels. Furthermore, to allow valid comparison between spaced and unspaced conditions, (a) landings on the space were omitted from the analysis in the case of the spaced script condition and (b) landings launched from the last character of the preceding word were omitted for the unspaced condition. Note that word centres were coded as zero pixels such that negative numbers represent the number of pixels that a landing site is to the left of word centre, and the more negative a number to further it is from word centre, and the closer to word onset.

In the resulting analysis (see Table 5), the word-initial character frequency was significant ($t = 2.323$; $p_{mcmc} = 0.02$), with the landing site closer to the word centre for high-frequency word-initial characters and closer to the word beginning for low-frequency word-initial characters. The overall mean landing site for first fixations on a word launched from the left was −2.0, just two pixels left of the word centre.

The presence of inter-word spaces played a significant and unsurprising role in modulating the effectiveness of the initial character in shifting the eye's landing position. As can be seen from Fig. 1, while there was a consistent across-the-board centring effect of high frequency initial character, this word-initial frequency effect was larger when spaces were present ($t = -2.052$, $p_{mcmc} = 0.04$) and this initial character frequency × spacing effect was further heightened when there were high word-final frequency characters ($t = 2.8$; $p_{mcmc} = 0.02$). In Fig. 1, both of the character frequency covariates appear to combine additively to improve the landing at the word centre and are facilitated by the presence of spaces – the best landing site results come from high-frequency initial and final characters in the presence of inter-word spaces. This suggests that the high-frequency characters act as stand-alone landmarks. If the effect were due to some general improvement in word identification, we would expect to see a more gradated effect across both high and low frequency characters.

Table 6
Correlations between bigram and character frequency measures.

	First character log frequency	Final character log frequency
Initial bigram log frequency	0.48	0.34
Final bigram log frequency	0.25	0.52

In the significant interaction shown in Fig. 2 between word frequency and spacing ($t = 2.921$, $p_{mcmc} = 0.003$), the presence of spacing improved the central targeting of low but not high frequency words because of what appears to be a ceiling effect – high frequency words seem to be centrally targeted irrespective of spacing. Moreover, when first character frequency was brought into the picture, this effect was significantly more effective for higher frequency words, as evidenced by a significant interaction between spacing, first character frequency, and word frequency ($t = -2.109$, $p_{mcmc} = 0.03$) (see Fig. 2).

While neither initial nor final bigram frequencies were significantly effective in their own right, they did interact significantly with a number of factors. However, in all cases bigram frequency appeared to act as a proxy for the corresponding character frequency measure. In this regard, recall that our bigram hypothesis is that if bigram frequencies are used for word targeting, we would expect to find that low-frequency bigrams should signal a word boundary and be associated with more accurate targeting. However, the significant interactions for bigram frequency (see Table 5) indicate the opposite effect. This is further supported by *positive* correlations between the two sets of covariates, the bigram and the character frequency measures (see Table 6). Thus the bigram effects that do exist appear to be due to the position-specific frequencies of the characters comprising the bigram pairs such that character frequency plays the key role in word targeting.

3.2. First fixation duration

First fixation durations were relatively unaffected by spacing or frequency variations in either boundary characters or bigrams (see Table 5). There was, however, a significant three-way interaction (spacing × initial bigram × final character frequency; $t = 2.2$, $p_{mcmc} = 0.03$; Fig. 3) whose underlying source is unclear. Fig. 3 shows a classic crossover interaction, with the pattern of

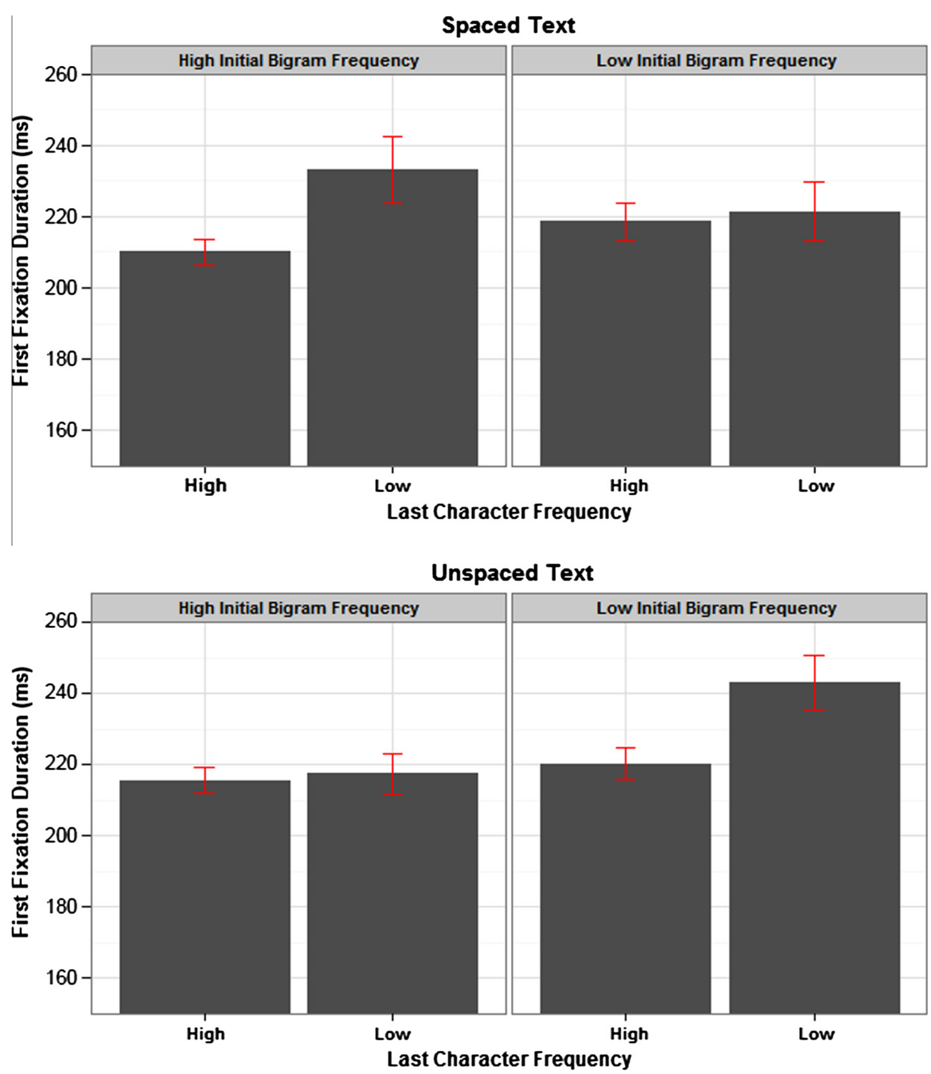

Fig. 3. First fixation durations in milliseconds as a function of word-initial bigram frequency, final character frequency, and spacing. Character and bigram frequency are dichotomised around their respective means.

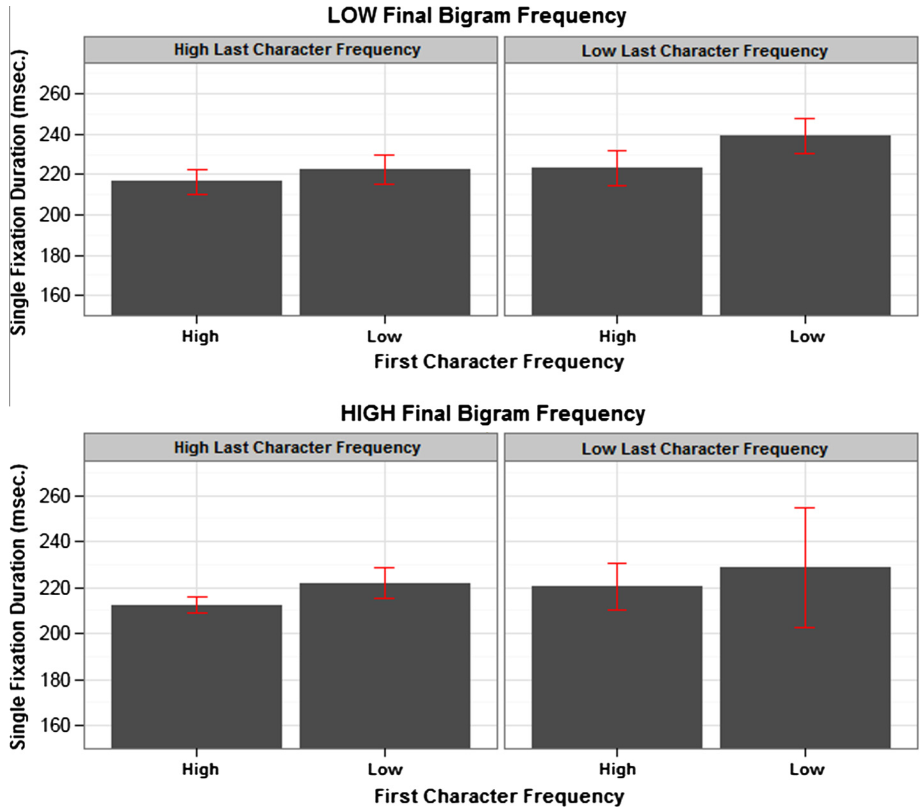

Fig. 4. Single fixation durations (first pass viewing time involving just a single fixation) in milliseconds as a function word-final bigram frequency and initial and final position-specific character frequency. Character and bigram frequency are dichotomised around their respective means.

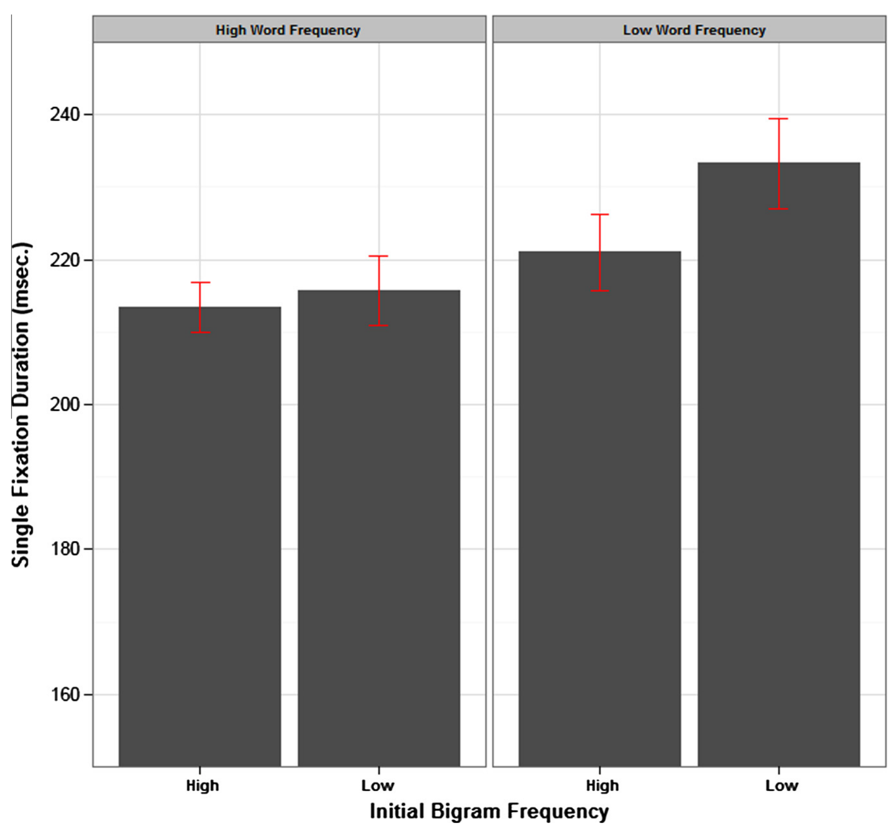

Fig. 5. Single fixation durations (first pass viewing time involving just a single fixation) in milliseconds as a function of word frequency and word-initial bigram frequency. Word and bigram frequency are dichotomised around their respective means.

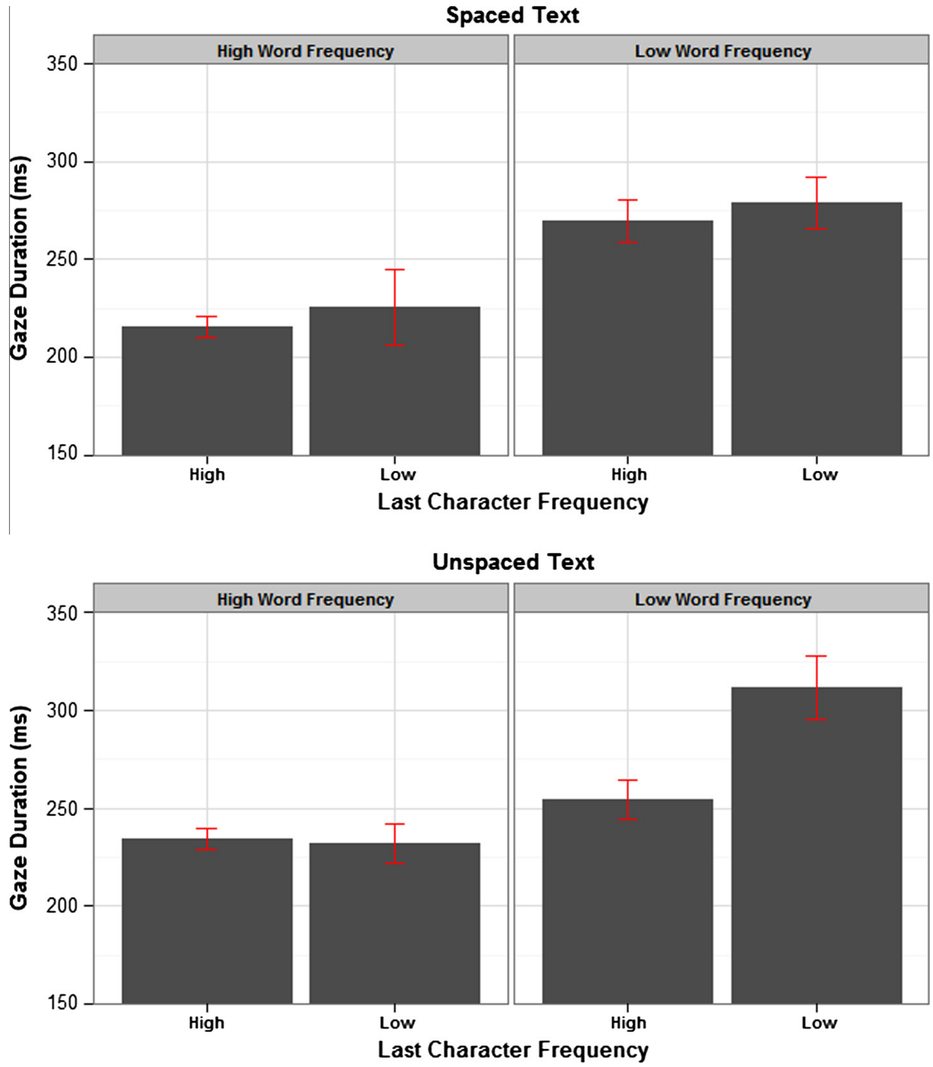

Fig. 6. Gaze durations (total of first pass fixations on a word) in milliseconds as a function of word frequency, final character frequency, and spacing. Word and character frequency are dichotomised around their respective means.

differences in the top row (spaced condition) reversing in the bottom row (unspaced condition).

3.3. Single fixation duration

The viewing time results from the single fixation analysis are more straightforward. The significant two-way interaction between first and last character frequency ($t = 2.39$, $p_{mcmc} = 0.01$) shows that there were shorter single fixations for words associated with high-frequency characters (see Fig. 4). This in turn gives rise to overall shorter single fixation durations where there are clues from both initial and final characters. The longest durations were associated with the complete absence of such clues and the resulting off-centre landings. There was also an interaction between first and last character frequency and final bigram frequency, but as can be seen in Fig. 4, the root of the interaction appears to be a large variance associated with one particular condition combination (low first and last character frequency and high final bigram frequency).

Finally, there was an interaction between initial bigram frequency and word frequency ($t = 2.01$, $p_{mcmc} = 0.04$; Fig. 5). In this case there was a typical slowing of fixation durations with lower frequency words, but with a high-frequency initial bigrams mitigating this effect for low frequency words.

3.4. Gaze duration

For the gaze duration measure there was a significant effect of initial character position-specific frequency, where the higher the character frequency the shorter the gaze duration ($t = 1.914$, $p_{mcmc} = 0.05$; 232 vs. 278 ms for above and below average frequency, respectively). This is understandable given that landing positions associated with high-frequency characters were more centred on the word and consequently support more rapid word recognition (see Fig. 1). The effect of word frequency was also significant, as was generally found for the gaze duration measure; high frequency words were viewed for shorter durations than words of low frequency ($t = -4.711$, $p_{mcmc} < 0.001$). Finally, there was a significant three-way interaction between spacing, final character frequency, and word frequency ($t = 2.848$, $p_{mcmc} = 0.004$). As can be seen from Fig. 6, the main source of the interaction is the shorter gaze duration for low frequency words with a high frequency end character when there are no inter-word spaces. It is unclear why the gaze durations should be comparatively shorter, particularly given the absence of spaces. Moreover, an examination of landing sites for that combination of conditions does not show any unusual pattern – the landing sites tend towards word beginning as with the other low word frequency conditions.

4. Discussion

The results of this study support the first two, but not the last two hypotheses proposed at the beginning of the paper. First, in line with earlier findings, the effective saccade target for Thai readers appears to be the word centre, with the mean landing site for first rightward incoming saccades just left of centre. Second, Thai readers seem to use characters that are diagnostic of word boundaries to help target word centres more effectively. The presence of high position-specific frequency characters in either word-initial or word-final positions serves to push the landing site further into the word than otherwise might be the case and also tends to shorten viewing times. This result confirms and extends similar findings by Reilly et al. (2005). The associated shorter viewing times can be accounted for by shorter fixation durations near word centres (O'Regan, 1990).

The third hypothesis was that low-frequency bigrams would serve to flag word boundaries, but this was not supported; in fact quite the reverse appears to be the case. When bigram frequency did have an effect on landing site, it did so as a proxy for the character frequency – presumably related to the frequencies of the pairs of characters making up the bigrams. Indeed, even when we controlled for character frequency by performing a separate analysis on just low-frequency boundary characters, there was no significant effect on landing sites due to the presence of boundary-diagnostic bigram. Because of channel capacity limitations it may not be feasible for the reader to simultaneously exploit information from bigram as well as character frequency. In the case of Thai, readers appear to have opted for the character frequency as a more reliable guide. In addition, another unexpected finding was the role that overall word frequency played in targeting word centres (see Fig. 2). This suggests that some sort of global word features, in addition to initial characters may come into play in word targeting.

The final hypothesis, that there would be a reading time advantage with inserted inter-word spaces was not supported. While there was a numerical advantage in the average gaze duration on words of just over 10 ms for the spaced condition, this did not translate into a statistically significant effect unless we omitted character frequency covariates from the model. This suggests that the root of the reading time advantage in spaced text may be the result of more visible word boundary characters and consequently more accurate word targeting.

The picture emerges, therefore, of Thai readers employing a flexible targeting system that makes opportunistic use of available statistical cues to the location of words and their centres – the position-specific frequencies of word-initial and word-final characters assist in directing Thai readers to an optimal viewing position just left of word centre. It remains for future research with young Thai readers or later readers learning Thai to determine the developmental course of the use of word boundary cues to facilitate optimal landing sites.

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