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Eye movements when reading spaced and unspaced Thai and English: A comparison of Thai–English bilinguals and English monolinguals

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ABSTRACT

The study investigated the eye movements of Thai–English bilinguals when reading both Thai and English with and without interword spaces, in comparison with English monolinguals. Thai is an alphabetic orthography without interword spaces. Participants read sentences with high and low frequency target words embedded in same sentence frames with and without interword spaces. Interword spaces had a selective effect on reading in Thai, as they facilitated word recognition, but did not affect eye guidance and lexical segmentation. Initial saccade landing positions were similar in spaced and unspaced text. As expected, removal of spaces severely disrupted reading in English, as reflected by the eye movement measures, in both bilinguals and monolinguals. Here, initial landing positions were significantly nearer the beginning of the target words when reading unspaced rather than spaced text. Effects were more accentuated in the bilinguals. In sum, results from reading in Thai give qualified support for a facilitatory function of interword spaces.

Seen from a dynamic visuomotor perspective, continuous reading involves two concurrent streams of processing. The primary stream is the processing of written language, where the acquisition of orthographically coded information feeds into the construction of a cognitive text representation. At the same time, the targeting and timing of saccadic eye movements serve to provide adequate spatio-temporal conditions for the extraction of text information. Research into the architecture and dynamics of information processing during reading has entered a new stage with the recent development of complex theories and computational models (see Engbert, Nuthmann, Richter, & Kliegl, 2005; Reichle, Rayner, & Pollatsek, 2003, for seminal discussions). However, the focus of these theoretical developments and the underlying empirical research has been on Indo-European languages such as English and German and relatively little work exists on reading of non-Roman scripts. In this context, Thai is particularly interesting as it has an alphabetic orthography, but does not naturally have interword spaces.

Spacing effects in Roman scripts

Visuomotor control in reading involves both spatial and temporal aspects. During each fixation it must be decided when and where the saccadic movement is to be executed. A large body of research has shown that eye movement control in alphabetic writing systems is largely word based. When a word is selected as the target for the ensuing saccade, a movement is programmed that aims at positioning the eyes at an "optimal viewing position" (OVP) (O'Reagan, 1990) close to the word center. However, due to visuomotor constraints, the actual landing positions of incoming initial saccades tend to peak at locations further to the left, between the word beginning and word center (McConkie, Kerr, Reddix, & Zola, 1988; Radach & McConkie,

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1998; Rayner, 1979). This phenomenon has been named the "preferred viewing location" (PVL) (Rayner, 1979) and is generally considered to be primarily determined by low level visual processing.

In Roman script, the spatial segmentation of words appears to be a major aid in guiding eye movements, as it allows parafoveal vision to parse text into an array of low spatial frequency word objects that can serve as saccade targets (McConkie et al., 1988). At the same time interword spaces also facilitate word identification, as they demarcate the boundaries of letter strings that are intended to correspond to lexical entities (Inhoff & Radach, 2002; Inhoff, Radach, & Heller, 2000; Rayner, Fischer, & Pollatsek, 1998). Based on these findings and other converging streams of evidence, the field has reached a consensus that both linguistic information processing and eye movement control are largely word based in Indo-European languages (Radach & Kennedy, 2004; Rayner, 1998).

Removing spaces in English typically slows reading by 30–50%, disrupting both the way the eyes move through the text and the word identification process (Morris, Rayner, & Pollatsek, 1990; Pollatsek & Rayner, 1982; Rayner et al., 1998; Spragins, Lefton, & Fischer, 1976). Rayner et al. (1998) observed that the masking or removal of interword spaces was more deleterious to the reading of (relatively unfamiliar) low frequency words than when reading length-matched (relatively familiar) high frequency words. They interpreted their results as indicating that removal of spaces interferes with word identification. Visuomotor control was also disrupted as indicated by substantial changes in the spatial distribution of incoming saccades over target words (landing site distributions). When interword spaces were present, these investigators found that readers tended to land a bit to the left of the middle of the word, whereas when spaces were removed they tended to land closer to the beginning. One possible explanation is that the lack of spaces does not provide an adequate target for the programming of a saccade into the word. A second possibility is that the initial landing position was altered by the greater difficulty that the participant had in processing the word (Rayner et al., 1998). In either case the lack of spaces appears to produce a substantially different pattern of eye movements when reading English. Juhasz, White, Liversedge, and Rayner (2008) have further suggested that parafoveal word length information can be used in combination with sentence context to narrow down the possible lexical candidates that are activated by an upcoming word.

Analogous experiments have been conducted on German and English compound words. Different spatial formats lead to different saccade targeting strategies, each of which is designed to land near the center of spatially distinct letter groupings (Inhoff & Radach, 2002; Inhoff et al., 2000). Insertion of illegal interword spaces in German compound words results in significantly shorter naming latencies and shorter first fixation durations and gaze durations than the normal unspaced condition. However, if the compound word was fixated three or four times then the last fixation on the compound word was actually longer in the spaced condition (Inhoff et al., 2000). Inhoff et al. (2000) concluded that the spaces facilitated lexical decomposition by providing a strong cue by which to segment words, but hindered readers' abilities to correctly compute the meaning of the compound words. Inhoff and Radach (2002) reported a similar experiment using hyphenation in place of spaces (e.g. Gehirnchirurg vs. Gehirn-Chirurg *brain surgeon*). Juhasz, Inhoff, and Rayner (2005) further examined the role of interword spaces when reading English compound words, which were normally nonspaced (softball) or normally spaced (front door) or with incorrect spacing (soft ball, frontdoor). They used both a lexical decision task and had participants read the words in sentences while their eye movements were recorded. For both types of compounds, lexical decision reaction times as well as error rates showed an advantage for the insertion of spaces, indicating that constituent processing was facilitated. For eye movements when reading, it was also found that there was a benefit of spatial segmentation for first fixation measures. However, when processing measures such as gaze duration (which incorporates refixations and later processes) were included, a cost due to spatial segmentation was revealed that was not apparent from examining the lexical decision data. Inserting a space into a normally nonspaced compound had a deleterious effect on these later processes, which again indicates that word comprehension was hindered by the abnormal insertion of spaces. These studies illustrate that eye movement measures can reveal time course processing differences and give information about how spatial segmentation and word recognition are affected by interword spacing, thus giving a picture of how word processing unfolds over time (Juhasz et al., 2005).

An important point to note is that assessing the function of spaces in English (or other Indo-European languages) is compromised by the fact that English readers are not familiar with unspaced text; hence it is hard to disentangle lack of training or habitual prior experience from real advantages of spatial segmentation.

Spacing effects in Chinese and Japanese

Some scripts, such as Chinese, Japanese and Thai, do not naturally have interword spaces. Intriguingly, facilitatory effects have been found when interword spaces have been inserted into Chinese (Hsu & Huang, 2000a; Hsu & Huang, 2000b) and also in Thai (Kohsom & Gobet, 1997, but not using eye movement methodology), even though that format is not the norm. There has been much debate as to whether eye movement control in Chinese and Japanese is word based, as results have been somewhat contradictory. Research conducted on Chinese by Yang and McConkie (1999) and Tsai and McConkie (2003) found no evidence that there is an equivalent to the preferred viewing position phenomenon in Chinese. They concluded that eye movement control in Chinese is neither word nor character based. The likelihood of fixating a character decreased monotonically from the first to the last character in a word, a finding that can be interpreted as a result of randomly sampling from a normal distribution of saccade amplitudes. However more recently, contradictory results have emerged. It has been found that Chinese readers, similar to English readers, fixate for less time on high frequency words than on low frequency words (Yan, Tian, Bai, & Rayner, 2006), and longer on low predictable words than on high predictable words (Rayner, Li, Juhasz, & Yan, 2005). Furthermore, they are more likely to skip highly predictable words in comparison with less predictable words (Rayner et al., 2005), and high frequency words more than low frequency words (Yan et al., 2006). Similarly, Yan, Richter, Shu, and Kliegl (2007) have found that when Chinese readers make a single fixation, they tend to initially fixate near the word center, and when they make multiple fixations, they fixate at the word beginning, with both tendencies occurring more often than would be predicted by random selection. Hence, recent research indicates that eye movement control in Chinese is word based.

Recent research has further investigated whether word units rather than individual characters are of primary importance when reading Chinese. Bai, Yan, Liversedge, Zang, and Rayner (2008) 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. As demarcating word boundaries with spaces resulted in faster reading times than the spaced single character condition, they concluded that word units rather than individual characters, are the unit of primary importance in Chinese reading. They proposed that there are two opposing forces that affect the reading of segmented Chinese text, facilitation of word processing and the detrimental effect that the unfamiliar visual text format has on reading. Additional support for the importance of word units for Chinese readers comes from Rayner, Li, and Pollatsek (2007) who recently successfully simulated the eye movement behavior of Chinese readers with the assumption built into the E-Z Reader model that words were the unit of analysis. In essence, recent research provides support for the view that words are important and have a psychological reality for Chinese readers, although not as prominent a role as in Roman script.

Similar research investigating the effect of spacing on reading has been conducted on Japanese. Written Japanese is naturally unspaced, and consists of three distinct scripts; Hiragana and Katakana (syllabic scripts), and Kanji (an ideographic script originating from Chinese). Sainio, Hyönä, Bingushi, and Bertram (2007) found that when reading "Hiragana-only" text, both word identification and eye guidance were facilitated by the insertion of interword spaces, but a mixture of Kanji–Hiragana (ideographic with syllabic) text was not facilitated by spaces. They also found an effect of spacing on initial landing positions in Hiragana, such that the eyes landed further into the word when reading spaced in contrast to unspaced text. Hence, results on Hiragana were in line with results from English (e.g. Rayner et al., 1998), although the facilitatory effects of spacing were considerably smaller than in English (12% in Hiragana compared to 30–50% in English). Sainio et al. (2007) suggest this difference is likely due to interword spaces not being the norm in Hiragana. Interestingly, they found script-specific processing differences when reading Japanese. For the mixed Kanji–Hiragana text they found a tendency for spaced text to be read slower than unspaced text, although this difference did not reach significance. Initial fixation landing position and the PVL for Kanji–Hiragana was also not affected by spacing. In both spaced and unspaced text the PVL was found to be in the word beginning, which is typically occupied by a perceptually salient Kanji character.

Comparisons between English and Chinese orthographies are potentially problematic as the Chinese writing system is predominantly logographic with most "characters" denoting units on the level of lexemes or morphemes. Information is much more densely packed in Chinese script, as most words include only two to three characters. These characters are often perceptually quite distinct and differ in visual complexity, pointing to the possibility that pre-attentive feature parsing may play a role in perceptual segmentation (see Wang, Inhoff, & Chen, 1999). In addition, there is some disagreement as to the location of word boundaries in Chinese text (Yang & McConkie, 1999). Japanese is also difficult to compare with English, as it includes a combination of three different types of script.

Reading in Thai

Thai offers an ideal opportunity to further empirically test the function of interword spaces because Thai script normally does not have interword spaces to indicate word or sentence boundaries. However, it is more comparable to English than Chinese because it is alphabetic. In a first exploratory study tracking eye movements in Thai, Reilly, Radach, Corbic, and Luksaneeyanawin (2005) collected data from Thai adults reading a short story. They found landing site distributions similar in shape but somewhat attenuated in comparison to those for readers of English or German, pointing to the possibility that oculomotor control in Thai is indeed word based. The current study represents the first attempt to study eye movements during reading in Thai in a controlled experimental setting, thus extending the empirical base of the field to accommodate a new writing system with some unique properties (see below). Specifically, our work examines the eye movements of Thai–English bilinguals when reading both Thai and English with and without interword spaces, and compares their eye movements in English reading to those of English monolinguals. Frequency of specific target words in the sentences is also critically manipulated as word frequency is considered to be a major determiner of the ease or difficulty of word identification and lexical access (Radach & Kennedy, 2004; Rayner, 1998). By manipulating both the availability of space information and word frequency, information can be gained about the effect of spacing on word identification.

If interword spaces play a crucial role in reading, then we can hypothesize that reading in Thai (as in English) will be facilitated when interword spaces are present. On a general level, overall reading rate should be faster in the spaced condition than in the unspaced condition. Following Rayner et al.'s (1998) study, we can assume that both eye movement control and word identification may be affected. More specifically, facilitation should manifest itself in eye movement measures both in terms of spatial parameters such as initial fixation positions and in viewing duration measures such as gaze duration and total reading time. In line with a large body of research, we can further expect a frequency effect, i.e. high frequency words will be read faster than low frequency words when reading both Thai and English (Rayner, 1998). If the facilitation hypothesis holds, and spatial segmentation is especially helpful when reading low frequency words, then the word frequency effect should be attenuated when spaces are present.

Alternatively, based on the fact that reading without spaces is the norm in Thai, and Thai adults have had extensive prior and habitual experience of reading text without interword spaces, we can predict that reading will be faster in the normal unspaced mode than in the spaced mode. Based on this argument, we can predict that insertion of spaces will interfere or have a deleterious effect on word identification, as well as eye movement control. An additional consideration is that there could be a selective effect: spacing may facilitate both eye guidance and early lexical decomposition by providing a strong visual cue by which to segment words. However, as it is a highly unusual text format in Thai it may also hinder readers' abilities to correctly compute the meaning of the word(s) in the sentences. Alternatively, word identification may be facilitated but eye movement control may be disrupted.

The design of the present study allows us to address a further theoretically interesting issue. It is possible that that there could be a positive transference of reading strategies from the Thai reader's first language to their second language, English, so that removal of spaces from English text would affect reading in the Thai–English bilinguals less than in the English monolinguals due to Thais being more experienced at reading text without interword spaces. There is general consensus that transfer does occur between writing systems, but what particular aspects of the writing systems are transferred and whether transference is positive or negative, is still much under debate (Koda, 2007). Cross-language transfer in reading has been defined as the ability to learn new reading skills in a second language by drawing on previously learned reading skills from the first language (Genesee, Geva, Dressler, & Kamil, 2006). It is feasible that over a life time Thai adult readers have developed a greater sensitivity for segmentation cues which could theoretically be transferred to reading English text without spaces. Alternatively, as Thai–English bilinguals have less experience and are less proficient in English than the monolinguals, we may predict that the effects of the spacing and word frequency manipulation will be more accentuated in the bilinguals than the monolinguals when reading English. Based on this argument, we can further expect this to be reflected in the relationship between English language ability and eye movement measures when reading English with spaced and unspaced text.

To summarize, the present paper presents the first experimental study involving eye movement analyses of reading in Thai, an alphabetic language written with no spaces between words. In addition to the specific goals outlined above, this work also serves the more fundamental purpose of broadening the empirical base for the ongoing debate on how the human mind masters the task of reading, given the constraints imposed by different writing systems (Radach & Kennedy, 2004; Radach, Reilly, & Inhoff, 2007; Rayner, 1998; Reichle & Laurent, 2006).

Method

Participants

Thirty-six Thai–English bilinguals/biscriptals were recruited from Chulalongkorn University, Bangkok, Thailand and tested at the Center for Research in Speech and Language Processing (CRSLP). Thirty-six comparison monolingual English speakers were recruited from the University of Western Sydney, Australia. English language background information and language ability was assessed using the Word Comprehension Antonyms and Synonyms subtests of the Woodcock Reading Mastery Tests-Revised (WRMT-R: Woodcock, 1998). The Thai participants' scores on this assessment were: $M = 26.03$ (39% correct), $SD = 6.29$, range 18–50 and the monolingual English participants' scores were: $M = 60.25$ (90% correct), $SD = 1.93$, range 57–65. All Thai participants were Thai native speakers/readers and were sequential bilinguals, i.e. they had learned Thai prior to learning English. The Thai participants' experience with English ranged from 9 to 20 years ($M = 14$ years). They first started learning English when they attended either preschool or school in Thailand. The majority of the students majored in languages or linguistics at university, and several were postgraduate students. They were paid for participation. The English participants were first year Psychology students, who were monolingual speakers of English. They participated in the study for course credit. All participants had normal or corrected-to-normal vision, and were naïve about the purpose of the experiment. Participants ranged in age from 18 to 28 years.

Materials

In both Thai and English, 72 sentences were created such that for each sentence both a high frequency and a low frequency target word fit semantically and syntactically into the same sentence position (similar to the method used by Rayner et al., 1998). The sentences in the two languages were not translations of one another. The target words were all nominals (refer to Fig. 1) and were always in medial position in the test sentences and never placed in the first or final two words. The high frequency and low frequency words were matched for length. Half of the words were five letters in length and half were six letters in length. Word frequencies were obtained from the Thai one million word database (Luksaneeyanawin, 2004) and English word frequencies were obtained from the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995). High

Thai sentences

HF **unspaced** คุณพ่อของฉันชอบรับประทาน**อาหาร**ที่มีรสจัด

spaced คุณพ่อ ของ ฉัน ชอบ รับประทาน **อาหาร** ที่ มี รสจัด

My father likes to eat **food** that is highly seasoned.

LF **unspaced** คุณพ่อของฉันชอบรับประทาน**น้ำพริก**ที่มีรสจัด

spaced คุณพ่อ ของ ฉัน ชอบ รับประทาน **น้ำพริก** ที่ มี รสจัด

My father likes to eat **chilli sauce** that is highly seasoned.

English sentences

HF **spaced** Early in the morning the **agent** signed the contract.

unspaced Earlyinthemorningthe**agent**signedthecontract.

LF **spaced** Early in the morning the **clown** signed the contract.

unspaced Earlyinthemorningthe**clown**signedthecontract.

Fig. 1. Example of the test sentences used in Thai and English (target words are in bold).

frequency Thai words ranged in frequency from 52 to 1822 words per million, $M = 318$ per million, whereas the low frequency words were selected from the frequency range of 2–52 words per million, $M = 36$ per million. High frequency English words ranged from 54 to 827 words per million, $M = 131$ per million and the low frequency words were selected in the frequency range 1–10 per million, $M = 4$ words per million. The different word frequency selections reflect differences between the distribution characteristics of the two languages. For the Thai sentences interword spaces were inserted into the test sentences by two Thai linguists, such that there was mutual agreement on word segmentation in all sentences.

The sentences for each language were divided into four lists. Each sentence frame appeared twice on a list, once with spaces between the words and once without. In each spacing condition, half of the target words were high in frequency and half were low in frequency. Each list contained 144 sentences with 36 sentences in each of the four experimental conditions. The stimuli were rotated across the lists in a Latin-square design. That is, within a spacing condition, participants saw a particular sentence frame with either the high frequency or the low frequency target word, but not both. Furthermore, if a particular sentence frame in one spacing condition contained the high frequency target word, then in the other spacing condition it contained the low frequency target word. Therefore, each target word appeared only once on a list.

Apparatus

The test stimuli were presented using the EyeLink II tracking system (SR Research Canada). The eye tracker is an infrared video based tracking system. It has two cameras for each eye with two infra-red LEDs for illuminating each eye mounted on a headband. The cameras sample pupil location at a rate of 250 Hz; equivalent to a temporal resolution of 4 ms. The eye tracker monitored movements of the right eye, although viewing was binocular. Participants were seated 61 cm away from a computer screen and silently read single line sentences. Sentences were displayed on a single line of the computer screen in Courier 14 point (Thai) or 12 point (English) font. Although the font size differed between the two languages, the letter sizes were approximately equal. From a viewing distance of 61 cm from the computer screen, three letters occupied approximately one degree of visual angle.

Procedure

At the beginning of the experiment, the eye-tracking system was calibrated for the participant. Each trial started with a fixation point on the left-hand side of the monitor, the location of which coincided with the location of the first letter in the sentence. The participant was instructed to look at the fixation point and then the sentence was presented. Participants were instructed to read for comprehension and to press a response key as soon as they finished reading the sentence. Sentence reading latencies were calculated from the appearance of the sentence on the screen until the key press.

Each participant read 12 practice trials followed by 144 experimental trials. Sentences were presented in a fixed random order. Comprehension was checked on approximately 10–15% of trials during the experiment by presenting participants with a question which could be answered by yes or no. Accuracy was over 96%.

Thai–English bilinguals read sentences in both English and Thai; the order of presentation was counterbalanced. They were also given a background information questionnaire to complete and assessed for English reading and vocabulary knowledge. Thai participants completed the second list on a subsequent day. English monolinguals completed only a list of English trials.

Results

Eye movement measures can give a picture of how word processing unfolds over time, hence several processing measures were computed at the sentence and target word levels (see Juhasz et al., 2005, for a discussion in the context of spacing effects). For sentence level measures, total sentence reading time and fixation count measures were computed. At the target word level, first fixation duration, gaze duration, total viewing fixation duration, and first fixation landing position served as dependent measures. First fixation duration is the duration of the first fixation on the target word, irrespective of other additional fixations occurring on the target word. Gaze duration is the sum of all fixations on the target region prior to moving to another word. Total viewing fixation duration consisted of the cumulated fixation durations on the target word in the whole trial including time spent re-reading the critical word. To determine whether occulomotor control in Thai is word based, a further dependent measure was initial landing position. Initial fixation landing position refers to the letter on which the eyes initially land within the target word (see Inhoff & Radach, 1998; Radach & Kennedy, 2004; Rayner, 1998 for definitions and discussions of oculomotor measures). Separate sets of analyses were conducted on data from Thai participants reading in Thai, Thai participants reading in English, and English participants reading in English.

Sentence measures

In order to examine the effect of the spacing manipulation on sentence reading, repeated measures analyses of variance (ANOVAs) were performed on sentence reading times and fixation counts using both participant (F_1) and item means (F_2) as units of analysis (see Table 1 for means).

Reading with and without interword spaces in Thai

Participants had longer sentence reading times when reading spaced sentences in Thai than when reading unspaced sentences, ($F_1(1, 35) = 4.03$, $p = .05$, $\eta_p^2 = .103$, $F_2(1, 143) = 5.49$, $p < .05$, $\eta_p^2 = .038$, $minF'(1, 93) = 2.32$, $p = .13$), and they made more fixations when reading spaced sentences, ($F_1(1, 35) = 13.97$, $p < .01$, $\eta_p^2 = .285$, $F_2(1, 143) = 14.49$, $p < .01$, $\eta_p^2 = .077$, $minF'(1, 110) = 7.11$, $p < .01$). There was a 5% decrement in reading rate when spaces were introduced into the text. Reading times may have been longer in the spaced condition because the sentences were 12.8% longer than in the unspaced condition.

Thai–English bilinguals reading with and without interword spaces in English

The Thai participants had longer sentence reading times when reading unspaced sentences in English than when reading spaced sentences, ($F_1(1, 35) = 145.90$, $p < .001$, $\eta_p^2 = .807$, $F_2(1, 143) = 496.10$, $p < .001$, $\eta_p^2 = .780$, $minF'(1, 57) = 112.70$, $p < .001$), and they made more fixations when reading unspaced sentences, ($F_1(1, 35) = 298.75$, $p < .001$, $\eta_p^2 = .681$, $F_2(1, 143) = 211.78$, $p < .001$, $\eta_p^2 = .602$, $minF'(1, 137) = 123.92$, $p < .001$). There was a 45% decrement in reading rate in the unspaced condition.

Monolinguals reading with and without interword spaces in English

The English monolingual participants had longer sentence reading times when reading unspaced sentences in English than when reading spaced sentences, ($F_1(1, 35) = 147.01$, $p < .001$, $\eta_p^2 = .808$, $F_2(1, 143) = 409.85$, $p < .001$, $\eta_p^2 = .745$, $minF'(1, 63) = 108.19$, $p < .001$), and they made more fixations when reading unspaced sentences, ($F_1(1, 35) = 72.21$, $p < .001$, $\eta_p^2 = .674$, $F_2(1, 143) = 211.78$, $p < .001$, $\eta_p^2 = .602$, $minF'(1, 61) = 53.85$, $p < .001$). There was an average of 33% decrement in reading rate in the unspaced condition. A repeated measures analysis of variance was conducted to examine the effect of spacing on bilinguals' in comparison with monolinguals' reading rates. Language group (bilinguals and monolinguals) was a between-participants factor. There was a significant interaction effect between language group and spacing, ($F_1(1, 70) = 23.81$, $p < .001$, $\eta_p^2 = .254$) indicating that deleting spaces in English sentences had a larger impact on the reading speed of Thai compared to English participants.

Target word measures

Data were excluded from trials on which the first fixation duration was less than 80 ms, since short fixations do not seem to reflect cognitive processing of the target word (Lee, Rayner, & Pollatsek, 2001; Rayner, 1998), and

Table 1
Sentence reading measures for Thai–English bilinguals reading Thai and English, and monolinguals reading English (means and standard deviations). Only standard deviations are in parentheses.

	Thai–English bilinguals reading Thai		Thai–English bilinguals reading English		Monolinguals reading English	
	Spaced	Unspaced	Spaced	Unspaced	Spaced	Unspaced
Sentence reading time (ms)	1834 (670)	1746 (648)	2133 (688)	3887 (1742)	1827 (657)	2730 (1173)
Fixation count	9.27 (2.91)	8.62 (2.83)	10.25 (2.88)	15.05 (5.86)	9.00 (2.48)	11.66 (4.34)

if the target word was skipped or there was tracking loss. This resulted in the removal of 13% of Thai–English bilinguals' Thai data, 8% of their English data, and 13% of the data from English monolinguals.

For each of the target word measures, 2 (spacing) $\times$ 2 (frequency) ANOVAs were conducted. Spacing and frequency were repeated measures in the analyses by participants. Spacing was also a repeated measure in the analyses by items, whereas frequency was a between-items variable. See Table 2 for the means for each of the three language conditions.

Thai–English bilinguals reading with and without interword spaces in Thai

A significant effect of spacing was not found for first fixation duration, (Fs < 1). However, readers' gaze durations and total fixation durations were longer on the target words in the unspaced than spaced sentences (gaze duration $F_1(1, 35) = 18.41$, $p < .001$, $\eta_p^2 = .345$, $F_2(1, 143) = 10.59$, $p < .01$, $\eta_p^2 = .070$, $minF'(1, 151) = 6.72$, $p < .05$, total fixation duration $F_1(1, 35) = 23.91$, $p < .001$, $\eta_p^2 = .406$, $F_2(1, 143) = 10.65$, $p < .01$, $\eta_p^2 = .071$, $minF'(1, 165) = 7.37$, $p < .01$). In addition, readers' fixation durations were longer on low frequency words than on high frequency words, (first fixation duration $F_1(1, 35) = 8.74$, $p < .01$, $\eta_p^2 = .200$, $F_2(1, 143) = 5.12$, $p < .05$, $\eta_p^2 = .035$, $minF'(1, 150) = 3.23$, $p < .05$, gaze duration $F_1(1, 35) = 29.44$, $p < .001$, $\eta_p^2 = .457$, $F_2(1, 143) = 12.01$, $p < .01$, $\eta_p^2 = .079$, $minF'(1, 169) = 8.53$, $p < .01$), and total fixation duration $F_1(1, 35) = 38.18$, $p < .001$, $\eta_p^2 = .522$, $F_2(1, 143) = 13.36$, $p < .01$, $\eta_p^2 = .087$, $minF'(1, 174) = 9.90$, $p < .01$). There was no interaction effect between spacing and word frequency for the fixation durations, first fixation duration (Fs < 1), gaze duration ($F_1(1, 35) = 1.86$, *ns*, $F_2(1, 143) = 1.05$, *ns*), and total fixation duration ($F_1(1, 35) = 2.07$, *ns*, $F_2 < 1$).

The facilitatory effect for spacing observed on target word data was in contrast to the slower sentence reading time found for spaced compared to unspaced text. One possible reason for this opposite pattern of results is that words are skipped more in the unspaced text. As reported previously, there were significantly fewer fixations on unspaced than spaced sentences. The mean skipping rate across entire sentences in each condition is not readily available because only target word boundaries were identified in the data files. However, the mean skipping rate for target words in the unspaced sentences (.12) was significantly higher than for target words in the spaced sentences (.09) in the items analysis ($t_1(36) = 1.95$, $p = .06$, $t_2(142) = 2.44$, $p < .05$). Closer examination of individual participants' sentence reading measures revealed that there are striking interindividual differences of spacing on reading. Fifteen participants had significantly longer reading times and a corresponding greater number of fixations when reading spaced sentences (reading time M = 1871 ms SD = 594, fixation count M = 9.21 SD = 2.32) than unspaced sentences (reading time M = 1586 ms SD = 506, fixation count M = 7.80 SD = 1.88), for 15 participants there was no significant difference when reading spaced (reading time M = 1839 ms SD = 435, fixation count M = 9.63 SD = 1.85) or unspaced (reading time M = 1836 ms SD = 414, fixation count M = 9.29 SD = 1.80) sentences, and six participants had significantly longer reading times and a greater number of fixations when reading unspaced sentences (reading time M = 1948 ms SD = 642, fixation count M = 9.03 SD = 2.22) than spaced sentences (reading time M = 1737 ms SD = 592, fixation count M = 8.47 SD = 2.08).

Thai–English bilinguals reading with and without interword spaces in English

Readers' fixation durations were longer on the target words in the unspaced than spaced sentences (first fixation duration $F_1(1, 35) = 171.87$, $p < .001$, $\eta_p^2 = .831$, $F_2(1, 143) = 170.11$, $p < .001$, $\eta_p^2 = .549$, $minF'(1, 113) = 85.49$, $p < .001$, gaze duration $F_1(1, 35) = 298.22$, $p < .001$, $\eta_p^2 = .895$, $F_2(1, 143) = 344.17$, $p < .001$, $\eta_p^2 = .711$, $minF'(1, 103) = 159.77$, $p < .001$, and total fixation duration $F_1(1, 35) = 321.44$, $p < .001$, $\eta_p^2 = .902$, $F_2(1, 143) = 341.50$, $p < .001$, $\eta_p^2 = .709$, $minF'(1, 108) = 165.58$, $p < .001$). In addition, readers' fixation durations were longer on low frequency words than on high frequency words, (first fixation duration $F_1(1, 35) = 16.43$, $p < .001$, $\eta_p^2 = .320$, $F_2(1, 143) = 13.32$, $p < .001$, $\eta_p^2 = .087$, $minF'(1, 127) = 7.36$, $p < .01$, gaze duration $F_1(1, 35) = 43.49$, $p < .001$, $\eta_p^2 = .554$, $F_2(1, 143) = 32.84$, $p < .001$, $\eta_p^2 = .190$, $minF'(1, 132) = 18.71$, $p < .001$, and total fixation duration $F_1(1, 35) = 51.83$, $p < .001$, $\eta_p^2 = .597$, $F_2(1, 143) = 36.21$, $p < .001$, $\eta_p^2 = .205$, $minF'(1, 138) = 21.31$, $p < .001$). There was a marginal interaction effect between spacing and word frequency for total fixation duration for the participant analysis ($F_1(1, 35) = 3.95$, $p = .055$, $\eta_p^2 = .101$, $F_2(1, 143) = 2.80$, *ns*), but not for first fixation duration or gaze duration (Fs < 1). As can be seen in Table 2, for total fixation durations the frequency effect was larger in the unspaced condition compared to the spaced condition.

Monolinguals reading with and without interword spaces in English

Readers' fixation durations were longer on the target words in the unspaced than spaced sentences (first fixation duration $F_1(1, 35) = 92.40$, $p < .001$, $\eta_p^2 = .725$, $F_2(1, 143) = 146.70$, $p < .001$, $\eta_p^2 = .512$, $minF'(1, 85) = 56.69$, $p < .001$, gaze duration $F_1(1, 35) = 231.75$, $p < .001$, $\eta_p^2 = .869$, $F_2(1, 143) = 219.49$, $p < .001$, $\eta_p^2 = .611$, $minF'(1, 116) = 112.72$, $p < .001$, and total fixation duration $F_1(1, 35) = 255.57$, $p < .001$, $\eta_p^2 = .880$, $F_2(1, 143) = 215.06$, $p < .001$, $\eta_p^2 = .606$, $minF'(1, 125) = 116.78$, $p < .001$). In addition, readers' fixation durations were longer on low frequency words than on high frequency words, (first fixation duration $F_1(1, 35) = 11.58$, $p < .01$, $\eta_p^2 = .249$, $F_2(1, 143) = 9.07$, $p < .01$, $\eta_p^2 = .061$, $minF'(1, 130) = 5.09$, $p < .05$, gaze duration $F_1(1, 35) = 11.61$, $p < .001$, $\eta_p^2 = .249$, $F_2(1, 143) = 10.51$, $p < .01$, $\eta_p^2 = .070$, $minF'(1, 119) = 5.52$, $p < .05$, and total fixation duration $F_1(1, 35) = 12.64$, $p < .001$, $\eta_p^2 = .265$, $F_2(1, 143) = 12.19$, $p < .01$, $\eta_p^2 = .080$, $minF'(1, 115) = 6.21$, $p < .05$). There was a slight indication of an interaction effect for gaze duration for the participant analysis ($F_1(1, 35) = 2.98$, $p = .093$, $\eta_p^2 = .078$, $F_2(1, 143) = 1.28$, *ns*), but not for first fixation duration or total fixation duration (Fs < 1).

Initial landing position on target words

In order to examine the effects of spacing and frequency on oculomotor control, initial first fixation landing position

Table 2
Target word measures for Thai–English bilinguals reading Thai and English, and monolinguals reading English (means and standard deviations in milliseconds). Only standard deviations are in parentheses.

	Thai–English bilinguals reading Thai				Thai–English bilinguals reading English				Monolinguals reading English			
	Spaced		Unspaced		Spaced		Unspaced		Spaced		Unspaced	
	High frequency	Low frequency	High frequency	Low frequency	High frequency	Low frequency	High frequency	Low frequency	High frequency	Low frequency	High frequency	Low frequency
First fixation duration	200 (64)	208 (74)	202 (60)	210 (66)	220 (70)	235 (85)	276 (108)	292 (129)	204 (65)	213 (72)	240 (81)	249 (85)
Gaze duration	224 (94)	240	239 (109)	273 (161)	254 (106)	301 (142)	418 (205)	474 (235)	221 (91)	237 (104)	322 (179)	353 (181)
Total fixation duration	245 (120)	270 (162)	268 (139)	309 (175)	282 (140)	340 (184)	499 (265)	593 (308)	239 (112)	262 (128)	359 (195)	398 (202)

patterns were examined when reading Thai and when reading English.

Reading Thai with and without interword spaces

The mean first fixation landing position on target words was not influenced by whether the words appeared in spaced or unspaced sentences, ($Fs < 1$) (see Table 3). There was also no significant effect of target word frequency, ($Fs < 1$). Mean first fixation landing position in both the spaced and unspaced condition was just left of center of the word (approximately 0.3 of a letter).

Fig. 2a shows the distribution of the initial landing positions on the target words during sentence reading. To allow for comparisons across different word lengths (five and six letter words), the data are presented relative to the center of the word (e.g. letter 3 in a 5-letter word and letter position 3.5 in a 6-letter word). The landing distributions for reading spaced and unspaced text in Thai display similar profiles. These results indicate that eye guidance and lexical segmentation are neither facilitated nor disrupted by the insertion of spaces into Thai text.

Reading English with and without interword spaces

In order to compare initial landing positions in the bilinguals and monolinguals when reading spaced and unspaced text in English, a mixed repeated measures analysis of variance (ANOVA) with language group (monolinguals, bilinguals) as a between-participants factor and spacing (with, without) and frequency (high, low) as within-participant factors was conducted. There was a significant effect of language group, ($F(1, 70) = 4.46$, $p < .05$, $\eta_p^2 = .060$). The monolinguals had initial landing positions closer to the mid-word position than the bilinguals. There was a significant effect of spacing, ($F(1, 70) = 89.92$, $p < .001$, $\eta_p^2 = .562$), as in the spaced condition initial landing positions were closer to mid-word position than in the unspaced condition. There was a significant interaction of language group by spacing, ($F(1, 70) = 26.06$, $p < .001$, $\eta_p^2 = .271$). In the spaced condition, the landing position was just left of the center position of the word (approximately 0.3 of a letter) for both language groups, which corresponds to the PVL. In the unspaced condition, the landing position was closer to the word beginning in the bilinguals (approximately 0.9 of a letter away from mid-word position) and to a lesser extent in the monolinguals (approximately 0.5 of a letter from mid-word position). There was no effect of frequency, ($F < 1$). However, there was a significant interaction of language group by frequency, ($F(1, 70) = 8.18$, $p < .01$, $\eta_p^2 = .105$). In the bilinguals, landing position was closer to the beginning in low frequency target words than in high frequency words ($t(35) = 2.71$, $p = .01$), whereas in monolinguals, frequency had no impact on landing position ($t(35) = -1.10$, *ns*).

The distributions of initial landing positions on target words are presented in Fig. 2b (Thai–English bilinguals) and Fig. 2c (English monolinguals). Similar trends are reflected in the initial landing site distributions of the bilinguals and monolinguals, as initial landing position is closer to the word beginning in the unspaced condition than in the spaced condition. This is more accentuated in the bilinguals than monolinguals.

Table 3
Mean initial landing positions for the Thai–English bilinguals (reading Thai and English) and the English monolinguals for spaced and unspaced text with high frequency (HF) and low frequency (LF) target words (initial landing position is given as distance from mid-word position (OVP) in tenths of a letter).

	Thai–English bilinguals reading Thai		Thai–English bilinguals reading English		English monolinguals reading English	
	HF	LF	HF	LF	HF	LF
Spaced	−.34 (.03)	−.40 (.03)	−.28 (.03)	−.46 (.04)	−.45 (.04)	−.41 (.04)
Unspaced	−.34 (.04)	−.29 (.03)	−.82 (.03)	−.93 (.03)	−.59 (.04)	−.53 (.04)

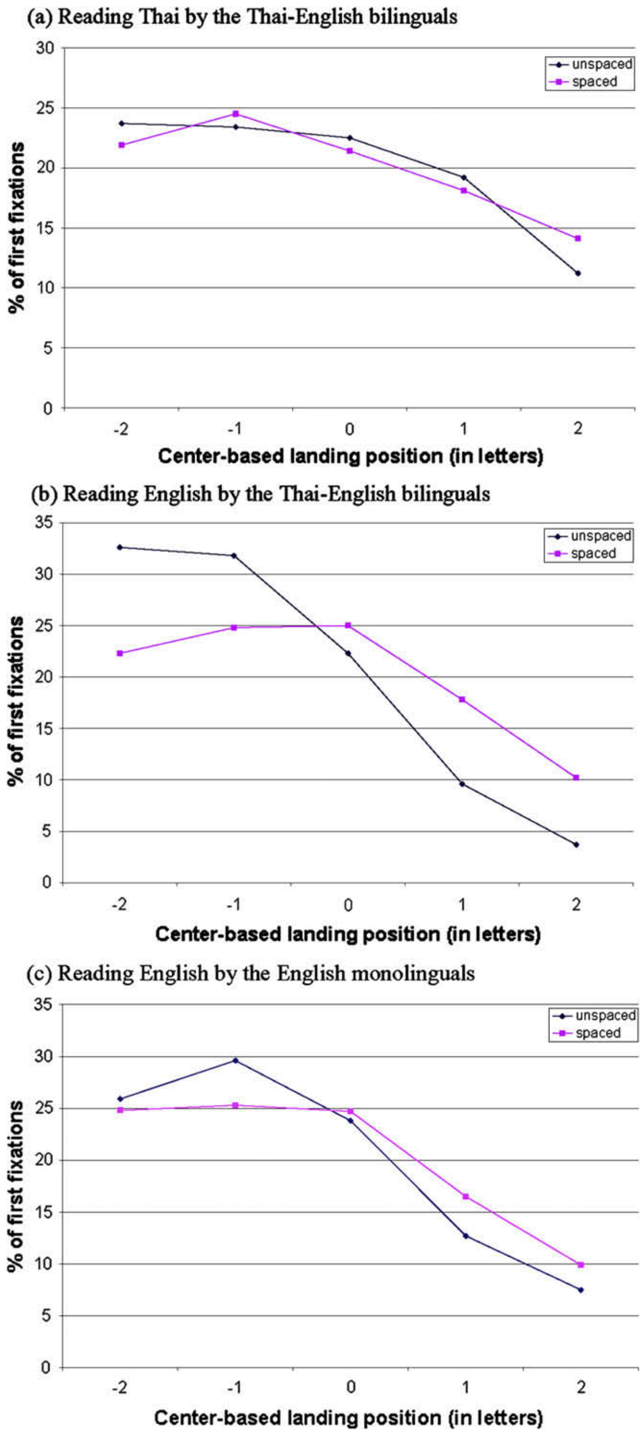

Fig. 2. Percentage of first fixations landing at each of five letter positions when reading spaced and unspaced Thai and English sentences.

In sum, the monolinguals and bilinguals display similar landing site distribution profiles when reading English text with and without spaces. Both the monolinguals and bilinguals when reading English have a tendency to land closer to the word beginning in the unspaced than spaced conditions. However, reading is more disrupted by the removal of spaces in the bilinguals than the monolinguals.

Relationship between English ability and eye movement measures

It was expected that the reading measures would be influenced by English language ability. In order to ascertain if there was a relationship between the eye movement measures and English language ability, a series of Pearson's product moment correlations were conducted between English language ability and the target word eye movement measures when reading English in the Thai–English bilinguals. As the English monolinguals reached ceiling on the English language ability assessment, their data were not included in this analysis. In the Thai–English bilinguals, there were significant positive correlations between English language ability and initial landing position in the spaced condition $r(35) = .423$, $p < .05$, and with initial landing position in low frequency words $r(35) = .373$, $p < .05$. These results suggest that higher English language ability is associated with initial landing positions nearer to the middle of the word, equivalent to the PVL or OVP in spaced text, and nearer mid-position in low frequency target words.

In addition, there were significant negative correlations between English language ability and gaze duration for low frequency target words, $r(35) = -.343$, $p < .05$, and English language ability and total fixation duration for spaced and unspaced conditions ($r(35) = -.349$, $p < .05$; $r(35) = -.345$, $p < .05$, respectively), and for high frequency and low frequency target words ($r(35) = -.389$, $p < .05$; $r(35) = -.382$, $p < .05$, respectively). This indicates that lower English language ability is associated with longer gaze durations for low frequency words and longer total fixation durations. No other eye movement measures had a significant correlation with English language ability.

Discussion

In the current study, we investigated the function of interword spaces in reading in both Thai (which normally does not have interword spaces) and English (which does have interword spaces). Based on previous research, predominantly on Roman script, it is generally assumed that interword spaces serve a common facilitatory function because when spaces are removed eye movement control and word identification are substantially disrupted (Morris et al., 1990; Rayner et al., 1998; Spragins et al., 1976). Results from the English monolinguals confirm this conclusion. Interestingly, we observed here that adding spaces between Thai words shortened reading times on target words, even though Thai script does not naturally include such spaces. Several of our findings suggest that spacing facilitates later word processing rather than word targeting or early lexical segmentation. The effect of spacing on fixation durations was observed for measures that included refixations (gaze duration and total fixation time), but not for first fixation duration. Furthermore, first fixation landing positions and landing site distributions were not influenced by spacing. First fixation landing position in both the spaced and unspaced condition was just left of word center or the OVP. These results in conjunction with the lack of difference found for initial fixation duration, suggest that word targeting and early lexical segmentation is not facilitated (or disrupted) by the insertion of interword spaces, although later word processing including lexical access is substantially facilitated. As the initial position was just left of mid-word position on the target word, similar to what typically occurs in Roman script, these results also confirm Reilly et al. (2005) pilot work, suggesting that occulomotor control in reading in Thai is word based.

Frequency of specific target words in the sentences was also manipulated as word frequency is considered to be a major determiner of the ease or difficulty of word identification and lexical access (Radach & Kennedy, 2004; Rayner, 1998). An across the board word frequency effect was found. We also expected the frequency effect to be attenuated in the spaced compared to the unspaced condition. For Thai, there was no effect. For reading English, there was only a marginal interaction effect for total fixation for the bilinguals, and only a slight indication of an interaction effect for gaze duration for the monolinguals. Rayner et al. (1998) also only found a marginal interaction effect for gaze duration in Experiment 1 with similar manipulations as in the current study. These results give only weak support to the proposition that lexical access is facilitated by interword spaces. However, the gaze duration and total fixation duration measures do give support, and are considered reliable time course processing measures and indicators of later lexical access (Inhoff et al., 2000; Juhasz et al., 2005).

The question arises as to why we did not find an advantage of spacing for parameters at the sentence level. In fact, there was a slight (marginally significant) increase in overall sentence reading time together with a significantly larger overall number of fixations on the line of text in the spaced than the spaced condition. When Thai text is segmented, the constituents may become visually distinct targets that attract fixations, irrespective of an advantage for word recognition (Inhoff & Radach, 2002). This hypothesis is also supported by the fact that skipping rate was higher for target words in the normal unspaced format than the spaced format. An additional consideration is that in the spaced condition the sentences were 12.8% longer than in the unspaced condition, which could also affect the global reading measures.

Bai et al. (2008) proposed that two opposing forces, facilitation of word processing and the detrimental effect on reading of the unfamiliar visual text format are at play when Chinese text is segmented, leading to approximately equal global reading rates in both spaced and unspaced conditions. In both Thai and Chinese, it can be assumed that reading skill and practice changes the balance between word processing benefit and visuomotor cost to word spacing. Quite striking individual differences in the effect of spacing on global reading measures were found between Thai participants. Some participants' global reading measures were deleteriously affected by the unusual spaced format (42%), yet the reading of other participants was either facilitated (16%) or not affected (42%). Clearly, a more detailed examination of interindividual differences when reading Thai segmented text is required. We need to examine the effects of reading skill and practice on local and global reading measures in future research.

The results found for Thai have some similarities to results when reading mixed Hiragana–Kanji script with interword spaces inserted (Sainio et al. 2007). Results on reading Hiragana-only script were similar to English, as spaces facilitated both eye guidance and word identification. However, for the mixed Kanji–Hiragana text, Sainio et al. (2007) found a tendency for spaced text to be read slower than unspaced text, although this difference did not reach significance. In addition, similar to Thai, initial saccade landing positions for Kanji–Hiragana were not affected by spacing, although the PVL for the two languages was not the same. In the Japanese study, the PVL was found to be at the word beginning, which is typically occupied by a perceptually salient Kanji character, whereas the PVL for Thai was observed here to be just left of mid-word position.

In conclusion, the notion that interword spaces have a common facilitatory function is given qualified support by the Thai data reported in this study. Interword spaces have a selective facilitatory effect on reading in Thai, as word processing is facilitated, but eye guidance (word targeting and lexical segmentation) is not facilitated (or disrupted) by insertion of interword spaces. This main result is of general importance in the context of the ongoing theoretical debate on the nature of information processing during reading. When text is presented with visual segmentation cues like spaces, the boundaries of letter clusters forming lexical entities are clearly demarcated, thus providing a starting point for early word processing. In contrast, when an alphabetic writing system provides no spatial segmentation cues, determining the extent of the letter cluster forming a word becomes part and parcel (as opposed to a precondition) of initial word processing. Thus, although the general goal of reading, forming a mental representation of text, remains the same, the nature and order of processing operations necessary to attain this goal are substantially different. This is an important insight that needs to be taken into account in the future generation of computational models of continuous reading that aim to accommodate non-Roman writing systems (see Radach et al., 2007, for a review on such models).

Results for reading English concur with previous research (e.g. Rayner et al., 1998), as the removal of spaces severely disrupted reading in both the bilinguals and monolinguals. In the bilinguals, the removal of interword spaces had a larger effect on reading than in the monolinguals. First fixation duration and the refixation measures (gaze duration and total fixation duration) were deleteriously affected. The removal of interword spaces was more deleterious to the reading of low frequency words than high frequency words indicating that lack of spaces interferes with later word processing (Rayner et al., 1998). Visuomotor control was also disrupted as indicated by substantial changes in the spatial distribution of incoming saccades over target words. Both the monolinguals and bilinguals had a tendency to land closer to the word beginning in the unspaced than spaced condition. This effect was more pronounced in the bilinguals than the monolinguals, in particular for low frequency words. Furthermore, in the more proficient bilingual participants, there was a tendency to land nearer the PVL, particularly for low frequency target words. These results provide support for the suggestion that greater difficulty in processing words is associated with initial landing positions closer to the word beginning (Rayner et al., 1998). This account is in harmony with work showing that the orthographic familiarity of word beginnings has a small but significant effect on the initial landing position when reading in spatially segmented Roman script (e.g. Hyönä, 1995). As an example, Radach, Inhoff, and Heller (2004) employed a three level variation of orthographic regularity in German sentence reading to show that initial saccades are gradually more shifted to the right when moving towards more familiar initial letter clusters.

The Thai–English bilinguals' reading of the English sentences was more severely affected by removal of spaces than the monolinguals. There was a 45% decrement in reading rate in the bilinguals, but only 33% decrement in reading rate in the monolinguals. Hence, the prediction that there would be a positive transference effect when reading English due to their life time experience of reading Thai without spaces was not supported. It appears that language ability in the specific language being read affects performance more than prior experience with an unrelated orthography. Languages with different writing systems require different underlying processes, which sets limits on the transferability of such skills. Recent research using neuroimaging techniques indicates that in Chinese–English bilinguals there are shared regions as well as orthographic-specific regions of the brain activated when reading the two distinct orthographies (Perfetti et al., 2007). This may also be the case for Thai–English bilinguals.

In both Thai and English when reading unspaced text, readers must use other information than spaces to delineate word boundaries in the parafovea prior to word fixation. Experienced Thai readers are much more effective in solving this problem when they read in Thai than were either group of participants when they read in English. This is presumably due to unspaced text being the norm and having had a life time of experience reading text without spaces in Thai. At this point it is intriguing to speculate about the nature of the information used by Thai readers to delineate word boundaries in the absence of spacing. The fact that landing site distributions do not differ between spaced and unspaced text suggests that word segmentation is fast enough to mediate the programming of the initial saccade into a parafoveal target word. Thus, it appears likely that a relatively slow default mechanism of left to right scanning and lexical analysis can be accelerated with more immediate cues to segmentation (Bertram & Hyönä, 2003).

On a general level, an obvious candidate as a segmentation cue is the 'diagnosticity' of letter combinations (such as bigrams). In the case of Thai, Reilly et al. (2005) determined for their 2300 word text corpus the frequency that letters occurred at the beginning and end of words. They found that out of 74 characters, 10 accounted for an impressive 76.7% of all word end positions with the first three representing 44%. The corresponding numbers for word beginnings were 54.2% and 29.3%. This is quite encouraging in relation to future detailed analyses of statistical properties of letter combinations at word boundaries in Thai. Even more intriguing is the possibility that readers may acquire knowledge about *language-specific* word segmentation cues. An excellent example is the recent analysis of vowel quality properties at morpheme boundaries in Finnish, which has uncovered an intricate set of language-specific rules guiding the fast parsing of compounds (Bertram, Pollatsek, & Hyönä, 2004). In Thai, potential language-specific candidates for word or syllable segmentation are, for example, the vowels that occur prior to the consonant at the beginning of the syllable (e.g. โรค written as /o:rk/ but spoken as /ro:k/ *disease*), as they possibly form salient syllabic segmentation cues to the reader. In addition, tone markers that occur above the syllable or lexeme (e.g. หน้าต่าง /na:2ta:ŋ1/ *window* whereby 2 = a falling tone and 1 = a low tone) may form effective segmentation cues to the skilled reader. Support for this idea comes from the finding that when the tone markers for a target word were viewed in the parafovea prior to fixating that word, subsequent fixation durations on the target word were shorter (Winskel, under review).

When reading unspaced English the PVL was shifted closer to the word beginning, so the mechanism readers are using to segment text is not as effective as when reading normal unspaced Thai. However, this might theoretically be improved with practice at reading English without spaces, and there could be a corresponding shift towards the PVL. The fact that English monolinguals did not have the PVL shifted to the word beginning as much as the bilinguals when reading unspaced text, suggests that proficiency in the language is an important factor in recognizing word boundary cues and segmenting text without spaces.

References

Baayen, R. H., Piepenbrock, R., & Gulikers, L., (1995). *The CELEX lexical database (Release 2) [CD-ROM]*. Philadelphia: University of Pennsylvania, Linguistic Data Consortium.

Bai, X., Yan, G., Liversedge, S. P., Zang, C., & Rayner, K. (2008). Reading spaced and unspaced Chinese text: Evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance, 34*, 1277–1287.

Bertram, R., & Hyönä, J. (2003). The length of a complex word modifies the role of morphological structure: Evidence from reading short and long Finnish compounds. *Journal of Memory and Language, 48*, 615–634.

Bertram, R., Pollatsek, A., & Hyönä, J. (2004). Morphological parsing and the use of segmentation cues in reading Finnish compounds. *Journal of Memory and Language, 51*, 325–345.

Engbert, R., Nuthmann, A., Richter, E., & Kliegl, R. (2005). SWIFT: A dynamical model of saccade generation during reading. *Psychological Review, 112*, 777–813.

Genesee, F., Geva, E., Dressler, C., & Kamil, M. L. (2006). Synthesis: Cross-linguistic relationships. In D. August & T. Shanahan (Eds.), *Developing literacy in second-language learners: Report of the National Literacy Panel on language-minority children and youth* (pp. 153–183). Mahwah, NJ: Erlbaum.

Hsu, S.-H., & Huang, K.-C. (2000a). Effects of word spacing on reading Chinese text from a video display terminal. *Perceptual & Motor Skills, 90*, 81–92.

Hsu, S.-H., & Huang, K.-C. (2000b). Interword spacing in Chinese text layout. *Perceptual & Motor Skills, 91*, 355–365.

Hyönä, J. (1995). Do irregular letter combinations attract readers' attention? Evidence from fixation locations in words. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 68–81.

Inhoff, A. W., & Radach, R. (1998). Definition and computation of oculomotor measures in the study of cognitive processes. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 29–54). Oxford: Elsevier.

Inhoff, A. W., & Radach, R. (2002). The role of spatial information in the reading of complex words. *Comments on Theoretical Biology, 7*, 121–138.

Inhoff, A., Radach, R., & Heller, D. (2000). Complex compounds in German: Interword spaces facilitate segmentation but hinder assignment of meaning. *Journal of Memory and Language, 42*, 23–50.

Juhasz, B. J., White, S. J., Liversedge, S. P., & Rayner, K. (2008). Eye movements and the use of parafoveal word length information in reading. *Journal of Experimental Psychology: Human Perception and Performance, 34*, 1560–1579.

Juhasz, B. J., Inhoff, A. W., & Rayner, K. (2005). The role of interword spaces in the processing of English compound words. *Language and Cognitive Processes, 20*, 291–316.

Koda, K. (2007). Reading and language learning: Cross-linguistic constraints on second language reading development. *Language Learning, 57*, 1–44.

Kohsom, C., & Gobet, F. (1997). Adding spaces to Thai and English: Effects on reading. *Proceedings of the Cognitive Science Society, 19*, 388–393.

Lee, H.-W., Rayner, K., & Pollatsek, A. (2001). The relative contribution of consonants and vowels to word identification during reading. *Journal of Memory and Language, 44*, 189–205.

Luksaneeyanawin, S. (2004). *Thai word frequency based on two million word corpus of written genre texts*. Bangkok, Thailand: Center for Research in Speech and Language Processing. Faculty of Arts. Chulalongkorn University.

McConkie, G. W., Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control during reading, I. The location of initial eye fixations on words. *Vision Research, 28*, 1107–1118.

Morris, R. K., Rayner, K., & Pollatsek, A. (1990). Eye movement guidance in reading: The role of parafoveal letter and space information. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 268–281.

O'Reagan, J.K. (1990). Eye movements and reading. In E. Kowler (Ed.), *Reviews of oculomotor research, vol. 4: Eye movements and their role in visual and cognitive processes* (pp. 395–453). Amsterdam: Elsevier.

Perfetti, C. A., Liu, Y., Fiez, J., Nelson, J., Bolger, D. J., & Tan, L.-H. (2007). Reading in two writing systems: Accommodation and assimilation of the brain's reading network. *Bilingualism: Language and Cognition, 10*, 131–146.

Pollatsek, A., & Rayner, K. (1982). Eye movement control in reading: The role of word boundaries. *Journal of Experimental Psychology: Human Perception and Performance, 8*, 817–833.

Radach, R., Inhoff, A. W., & Heller, D. (2004). Orthographic regularity gradually modulates saccade amplitudes in reading. *European Journal of Cognitive Psychology, 16*, 27–51.

Radach, R., & Kennedy, A. (2004). Theoretical perspectives on eye movements in reading. Past controversies, current deficits and an agenda for future research. *European Journal of Cognitive Psychology, 16*, 3–26.

Radach, R., & McConkie, G. W. (1998). Determinants of fixation positions in words during reading. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 77–100). Oxford: Elsevier.

Radach, R., Reilly, R., & Inhoff, A. W. (2007). Models of oculomotor control in reading: Towards a theoretical foundation of current debates. In R. van Gompel, M. Fischer, W. Murray, & R. Hill (Eds.), *Eye movements: A window on mind and brain*. Oxford: Elsevier.

Rayner, K. (1979). Eye guidance in reading: Fixation locations in words. *Perception, 8*, 21–30.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*, 372–422.

Rayner, K., Fischer, M. H., & Pollatsek, A. (1998). Unspaced text interferes with both word identification and eye movement control. *Vision Research, 38*, 1129–1144.

Rayner, K., Li, X., Juhasz, B. J., & Yan, G. (2005). The effect of word predictability on the eye movements of Chinese readers. *Psychonomic Bulletin & Review, 12*, 1089–1093.

Rayner, K., Li, X., & Pollatsek, A. (2007). Extending the E-Z reader model of eye movement control to Chinese readers. *Cognitive Science, 31*, 1021–1034.

Reichle, E. D., & Laurent, P. A. (2006). Using reinforcement learning to understand the emergence of intelligent eye movement behaviour during reading. *Psychological Review, 113*, 390–408.

Reichle, E. D., Rayner, K., & Pollatsek, A. (2003). The E-Z reader model of eye movement control in reading: Comparisons to other models. *Behavioral and Brain Sciences, 26*, 445–476.

Reilly, R. G., Radach, R., Corbic, D., & Luksaneeyanawin, S. (2005). Comparing reading in English and Thai – The role of spatial word unit segmentation in distributed processing and eye movement control. In *Proceedings of the 13th European conference on eye movements*, University of Bern, Switzerland, August 14–18, 2005.

Sainio, M., Hyönä, J., Bingushi, K., & Bertram, R. (2007). The role of interword spacing in reading Japanese: An eye movement study. *Vision Research, 47*, 2575–2584.

Spragins, A. B., Lefton, L. A., & Fischer, D. F. (1976). Eye movements while reading and searching spatially transformed text: A developmental perspective. *Memory & Cognition, 4*, 36–42.

Tsai, J-L., & McConkie, G. W. (2003). Where do Chinese readers send their eyes? In J. Hyönä, R. Radach, & H. Deubel (Eds.), *The mind's eye, cognitive and applied aspects of eye movement research*. Amsterdam: Elsevier.

Wang, J., Inhoff, A. W., & Chen, H.-C. (1999). *Reading Chinese script. A cognitive analysis*. Mahway, NJ: Erlbaum.

Winskel, H. (under review). Orthographic and phonological parafoveal processing of consonants, vowels, and tones when reading Thai. *Applied Psycholinguistics.*

Woodcock, R. W. (1998). *Woodcock reading mastery test – Revised* (WRMT-R). American Guidance Service.

Yan, M., Richter, E. M., Shu, H., & Kliegl, R. (2007). Reading Chinese script – The Beijing sentence corpus. In *Paper presented at the 14th European conference on eye movements*, Potsdam, Germany (August).

Yan, G., Tian, H., Bai, X., & Rayner, K. (2006). The effect of word and character frequency on the eye movements of Chinese readers. *British Journal of Psychology, 97*, 259–268.

Yang, H. M., & McConkie, G. W. (1999). Reading Chinese: Some basic eye movement characteristics. In J. Wang, A. Inhoff, & H. C. Chen (Eds.), *Reading Chinese script: A cognitive analysis* (pp. 207–222). Hillsdale, NJ: Erlbaum.