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Child readers' eye movements in reading Thai

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ABSTRACT

It has recently been found that adult native readers of Thai, an alphabetic *scriptio continua* language, engage similar oculomotor patterns as readers of languages written with spaces between words; despite the lack of inter-word spaces, first and last characters of a word appear to guide optimal placement of Thai readers' eye movements, just to the left of word-centre. The issue addressed by the research described here is whether eye movements of Thai *children* also show these oculomotor patterns. Here the effect of first and last character frequency and word frequency on the eye movements of 18 Thai children when silently reading normal 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 site location revealed that Thai children's eye movement patterns were similar to their adult counterparts. Both first character frequency and word frequency played important roles in Thai children's landing sites; children tended to land their eyes further into words, close to the word centre, if the word began with higher frequency first characters, and this effect was facilitated in higher frequency words. Spacing also facilitated more effective use of first character frequency and it also assisted in decreasing children's viewing time. The use of last-character frequency appeared to be a later development, affecting mainly single fixation duration and gaze duration. In general, Thai children use the same oculomotor control mechanisms in reading spaced and unspaced texts as Thai adults, who in turn have similar oculomotor control as readers of spaced texts. Thus, it appears that eye movements in reading converge on the optimal landing site using whatever cues are available to guide such placement.

1. Introduction

Reading, unlike speaking, requires specialised instruction, especially in the grapheme-to-phoneme conversion rules specific to the child's language. The age at which children begin formal schooling varies from 4 to 7 years, depending on the policy of the country. While age of reading instruction onset has some effect on reading acquisition, of more importance is the nature of the orthography and the grapheme-to-phoneme conversion rules (Goswami, 2005); acquisition and success in reading varies with the nature of orthography being learned (Seymour, Aro, & Erskine, 2003); languages with shallow (one-to-one) grapheme-phoneme correspondences are easier to learn to read than deep systems with many-to-one/one-to-many grapheme-phoneme correspondences (Seymour et al., 2003; Ziegler & Goswami, 2006).

Another essential aspect of reading is the development of the highly specialised eye movements that are necessary for reading efficiency and speed, and for effective meaning extraction. In contrast to grapheme-to-phoneme conversion rules, these are developed by beginning readers *without* explicit instruction. Nevertheless, there is extensive evidence that readers of left-to-right scripts with spaces between words converge upon a common strategy; they use those spaces to guide their eyes to the 'preferred viewing location' (PVL; Rayner, 1979) – a landing site about halfway between the word centre and word beginning (O'Regan, 1990; O'Regan, Levy-Shoen, Pynte & Brugaillere, 1984; Pollatsek & Rayner, 1982; Radach & Kennedy, 2004; Rayner, 1979; Rayner, 1998; White, 2008). This PVL is reasonably optimal with respect to the landing site which is most favourable for reading speed and accuracy, the optimal viewing position (OVP; O'Regan & Jacobs, 1992), which is just to the left of the word-centre.

There is much less research on alphabetic scripts that are *scriptio continua*, alphabetic writing systems with no spaces between words (see Kasisopa, Reilly, Luksaneeyanawin, & Burnham, 2013 for a review). However, recently it has been found that adult

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readers of the *scriptio continua* Thai script appear to make eye movements similar to those of readers of spaced scripts (Kasisopa et al., 2013; Reilly, Radach, Corbic, & Luksaneeyanawin, 2005). This paper follows on from these studies of Thai adults' reading and concerns the development of eye movements in reading by Thai children. Ahead of looking more specifically at the nature of oculomotor control in Thai adults and developmental studies of eye movements in reading, the distinctive features of the Thai writing system and details of literacy instruction in Thailand are set out.

2. The Thai script and literacy instruction in Thailand

Thai Orthography: The Thai writing system appears complicated but it is, in fact, quite consistent with relatively straightforward grapheme-to-phoneme conversion rules. Thai is written from left to right horizontally but with some vowel characters placed vertically above and/or below the main horizontal line and with all the tone characters placed above that line and above any upper vowels (see Fig. 1 below). Sequences of vowel characters in the main horizontal line can be written before, after, or bracketing the onset consonant character(s).

Thai is *scriptio continua* and this lack of spaces between words can lead to confusion in beginning first (L1) and second (L2) language readers. Word segmentation in Thai depends very strongly on sentential context, since many Thai character strings can be ambiguous. For example, “ตากลม” can be read as “ตาก-ลม” [tà:k lōm] (“exposed to wind”) or “ตา-กลม” [tā: klōm] (“round eyes”). To give a feel for Thai text, two example sentences are presented in Table 1.

With respect to grapheme-to-phoneme conversion, characters in the first character position are mostly shallow having a one-to-one correspondence with phonemes. In the last character position, on the other hand, there are a relatively small set of final phonemes in the Thai phonological system and the grapheme-to-phoneme correspondence is many-to-one.

According to the Thai Basic Education Curriculum B.E. 2544 (2001), the official age for Thai children to enter Grade 1 is around 7 years of age. However, Thai children normally attend kindergarten school for two to three years prior to this. Therefore, the usual age for Thai children to start formal education is 4–5 years of age, and moreover, Thai children officially learn alphabet character names in kindergarten. Teachers may also teach them to read some basic words such as those for colours, fruit, animals, days, and months, but linguistic knowledge and graphotactic rules are not taught until primary school (starting from Grade 1).

Thai Reading Instruction: In text books used to teach Thai children in Grades 1–6, lessons are based on the whole-word approach with additional phonic strategies to teach children how to map characters to sounds and gain a better understanding of the phonological realisation of different combinations of initial consonant classes and tone characters (Sirikanjanapong, 1996). Of particular relevance here is the fact that Thai children start learning to read text with inter-word spaces and continue with spaced text until almost the end of Grade 1; in the last chapter of the Grade 1 text, lessons change to the use of unspaced text. Examples of passages from Grade 1 and Grade 2 text books[1] are shown in Tables 2A and 2B respectively.

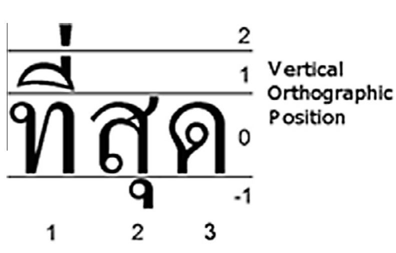

Fig. 1. Diagram showing orthographic positions in Thai.

3. Eye movements in reading Thai

Reilly et al. (2005) and Kasisopa et al. (2013) showed that the preferred viewing location (PVL) for Thai adult readers is just before the middle of the word. These studies showed that readers appeared to use the frequency of word boundary characters to land further into the word. These characters seemed to be cues to word beginnings and endings since some of them only occur in one or other of these positions. 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. Higher position-specific frequency of the first and of last characters significantly facilitated the eye landing close to the word centre. For example, Kasisopa et al. (2013) found that landing sites were closer to the centre of the word when word-initial characters had a high frequency of occurrence in that position. In addition, they found that when first character position-specific frequency was high, then the position-specific frequency of last characters also had an effect on facilitating landing positions near to the word centre.

So, despite the lack of inter-word spaces, Thai adults' landing site in words is just the same as their counterparts reading other scripts that have inter-word spaces. Thus, it appears that the position of the PVL is relatively consistent across alphabetic languages, despite the presence or otherwise of inter-word spaces. However, while there is pervasive use of boundary character frequencies to guide eye movements of experienced Thai readers (Kasisopa et al., 2013; Reilly et al., 2005), there is no indication, as yet, how this skill might develop in young readers of Thai. This is the focus of the current study.

4. Development of eye movements in reading

As in adult research, most studies of children's reading eye movements have investigated reading spaced alphabetic writing scripts. There are certain known developmental trends in eye movements in reading such scripts. Despite differences in procedures, for example, the manner in which eye movements are recorded, it has been consistently found that as reading skill increases fixation durations, frequency of fixations, and frequency of regressions decrease, while saccade length increases (e.g., Buswell, 1922; Hyönä & Olsen, 1995; Rayner, 1998). Correspondingly, it has also been found that, compared to adults, normally-developing children's average reading speed is slower, number of fixations is higher and saccade size is smaller (Hyönä & Olsen, 1995; Rayner, 1998; Rayner, Ardoin, & Binder, 2013).

Over and above these developmental trends, it has also been found that children's word fixation durations are negatively related to word frequency and positively related to word length (Blythe, Liversedge, Joseph, White, & Rayner, 2009; Hyönä & Olsen, 1995; Joseph, Liversedge, Blythe, White, & Rayner, 2009; Rayner et al., 2013). Children's eye movements in reading are also related to the level of transparency of the grapheme-to-phoneme correspondence rules in a particular language (Goswami, 2005; Rayner,

[1] All text books used to teach Thai subject in Thai primary and secondary school must be proved by Office of Basic Education Commission, Ministry of Education.

Table 1
Examples of Thai sentences (the sequences [tà: klōm] *versus* [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.]

1998); English language child readers' eye movements show the same PVL as adults even in their first year of reading, but there is a striking difference in refixations – children show a greater frequency of refixations before moving to the next word (McConkie et al., 1991).

Eye movements in reading are important developmentally, as there is a positive relationship between oculomotor control and reading ability. It has been found that children with poorer reading skills tend to have longer average fixation durations and a higher number of both progressive and regressive saccades (Søvik, Arntzen, & Samuelstuen, 2000). This relationship was also found by Huestegge, Radach, Corbic, and Huestegge (2009) who conducted the first longitudinal study of children's oculomotor control and linguistic development. German children showed an increase in global reading efficiency of 36% from second to fourth grade, and their comprehension increased from 79.95% to 84.84%. And as children's reading skill improved their oculomotor control improved, as shown by fewer fixations, shorter fixation durations (both first fixation and total gaze duration), reduced *percentage* of regressions, as well as increasing saccade length.

In a cross-script developmental study of eye movements in reading, Feng, Miller, Shu, and Zhang (2009) investigated orthographic effects on the development of reading in Chinese and English. Chinese and English differ in a number of ways including the linguistic unit orthographically represented, orthographic transparency, and the salience of visual cues for word boundaries. They found a similar pattern of development of eye movements in reading in the two languages – the number of fixations, fixation durations, as well as number of refixations decreased over age, while saccade size increased over age. Cross-script comparisons showed that the average number of fixations was significantly lower for Chinese child (but not adult) readers than for their English counterparts, but that fixation durations were similar across the two languages. English children showed significantly shorter forward saccades than Chinese children, and Chinese readers (both children and adults) showed more inter-word regressions than the English. Overall this study shows that there appears to be some (but not highly divergent) differences in oculomotor control between English and Chinese child readers but that these differences become somewhat ameliorated over development. These results thus suggest that, regardless of the differences in orthography, Chinese and English adult readers converge on similar oculomotor strategies as a product of more efficient and automated reading, with the effect of orthography on oculomotor strategies decreasing as reading skill increases.

It could be concluded that there is some convergence on the development of a set of oculomotor strategies in reading that are independent of the nature of the orthography, especially in mature and skilled readers. However, the generality of such a conclusion is as yet limited. Studies so far have investigated eye movements in children reading European spaced alphabetic writing systems or Asian *scriptio continua* ideographic writing systems (Blythe et al., 2009; Blythe et al., 2012; Feng et al., 2009; Joseph et al., 2009;

Table 2A
Text from Grade 1 Thai subject text book.

Thai	เวลา เทียง แดด ร้อน กล้า กับ จอม วิ่งเล่น ใน นา แก้ว กับ มะลิ นั่งเล่น ที ศาลา ท่าน้ำ
Phonetic transcription	[wē:lā: tʰî:aŋ dɛ̀:t rɔ̄:n klâ: kàp tɕɔ̄:m wîŋlên nāj nā: kɛ:w kàp málí nâŋlên tʰî: sǎ:lā: tʰâ:ná:m]
Translation	'At noon, even though it's hot Kla and Jom are playing and running in the rice field while Kaew and Mali play in the pavilion on the riverbank.'

Table 2B
Text from Grade 2 Thai subject text book.

Thai	คุณครูพูดว่า ''วันนี้แดดไม่ร้อน ลมพัดเย็นสบาย บนต้นไม้ก็มีนกน้อยมาอาศัย''
Phonetic transcription	[kʰūnkrū: pʰû:t wâ: wān ní: dɛ̀:t mâj rɔ̄:n lōm pʰát jēn sàbā:j bōn tônmâ:j kɔ̄: mī: nók nɔ̄:j mā: ʔā:sǎj]
Translation	'The teacher said ''The weather today is nice not too hot with cool breeze. There is a little bird living in the tree.'

Note: Spaces in the Thai text are punctuation to separate the phrases; ideas; or concepts

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

	IPA	%	cum%
First character			
เ	/e:/	10.9	10.90
น	/n/	8.1	19.00
ท	/tʰ/	6.7	25.70
แ	/ɛ:/	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

Rayner, Yang, Castelhano, & Liversedge, 2011; Rayner et al. 2013; Feng et al., 2009). There are no studies of the development of eye movements in reading a *scriptio continua* alphabetic writing system such as Thai. Given the finding that Thai adults' landing sites in words tend to approach the OVP based on first and last character frequency (Kasisopa et al., 2013; Reilly et al., 2005), and that this converges on the same eye placement strategy as their spaced text counterparts, it is of interest to investigate the development of Thai children's eye-movements in reading, and the degree to which these too might be a function of, or show a developmental trend towards, the use of first and last character frequencies to control optimal eye movements.

There are a number of points of interest in this study. First, it is important to investigate whether Thai children's eye movements mirror those of Thai adults. Do, for example, Thai children also have a PVL close to the word centre and, if so, is this governed by the frequency of first and last characters? Secondly, if there is a PVL effect, is this governed by the frequency of just the first character or by both first *and* last characters. That is, do Thai children have the same eye movement strategy as Thai adults or does the complex grapheme-phoneme realisation feature of final characters result in any diminished effect on their eye movement control? Thirdly, how does the transition from reading with spaces to without spaces affect Thai children's reading? If the results with Chinese (Blythe et al., 2012) generalise to Thai, then it might be expected that spaces may assist Thai children in terms of first fixation durations, and gaze, but that in other respects Thai children might show similar eye movement patterns when reading spaced and unspaced texts. More generally, the results of this study on reading development in an alphabetic *scriptio continua* script will have a bearing on indications mentioned above, that reading development in children may converge towards generally optimal principles irrespective of script type.

To these ends, a partial replication of Kasisopa et al. (2013) study was conducted to investigate Thai children's eye movements while silently reading sentences, written with or without spaces between words. Ideally, children in early primary school (1st and 2nd grades) and late primary school should have been tested, but the eye tracking apparatus (EyeLink II) was unsuitable for the small heads of students in 1st and 2nd grade. Thus two age groups were tested, younger children (tested at the start of Grade 6) and older children (tested towards the end of Grade 7). In order to allow comparison with adults, the study was modelled as much as possible on the design of the Kasisopa et al. (2013) study in which Thai adults' eye movements were investigated. Reading was investigated as a function of character frequency (high vs. low) in first and in last character positions, as well as the presence or absence of spaces between words. Thus, the study employed a factorial design comprising 2 age groups x 2 spacing conditions x 2 first character frequencies x 2 last character frequencies, with repeated measures on the last three factors.

The statistical analysis of eye movement data in this experiment involved the use of linear mixed-effects models (LMM) to analyse landing site location, first fixation duration, single fixation duration and gaze duration as the dependent variables, the same as in Kasisopa et al. (2013). The frequency of first and last character bigrams (see Kasisopa et al., 2013) were not used here in the model analysis of Thai children's eye movements, because Thai adults' results in Kasisopa et al. (2013) showed that the effects of bigram frequency seemed to be a proxy for stronger and more salient effects of character frequency itself. Moreover, and in support of this proxy argument, preliminary analysis of the children's eye movements here that included bigram frequency only showed significant effects when the character frequency in the same position was also significant.

5. Method

5.1. Participants

There were two age groups in this study, younger and older children, children at the start of 6th grade and at the end of their first year of secondary school (7th grade) respectively. Their guardians gave informed consent for them to participate in the experiment and received THB300 compensation for their participation. The study was conducted under University of Western Sydney Human Research Ethics Committee approval in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki).

There were eight participants in the older child group, all students who were about to finish the second semester of Grade 7 (mean = 12.7 years; range = 12–14 years). All of these older children successfully completed the tasks (see below). All of these older children were recruited from two of the top secondary schools in Bangkok, Thailand. There were initially 20 participants in the younger group, all of whom were just starting the first semester of Grade 6 (final year of primary school). Of these, only 15 completed the tasks (see below) and of these, eye movement data of only 10 could be used in the analysis – the fixation records of the other five participants' were far beyond the area of interest on the screen and could not be retrieved. The final sample of 10 younger children had a mean age of 11.4 years (range = 11–12 years). The children in this group were the children of university staff and attended public primary schools around Bangkok and nearby provinces. All subjects had normal vision.

5.2. Materials

There were two sets of materials, Stimulus Set 1 for the younger children (sentences comprised of words from Thai subject text books), and the more difficult Stimulus Set 2 for the older children. Set 2 stimuli were the same materials used to test the adult group in Kasisopa et al. (2013) and the sentences comprised of words used in every day reading materials such as news and magazines. Both stimulus sets comprised 20 practice sentences (18 familiarisation trials and two warm-up trials) and three blocks of 18 test trials (total = 54). In addition, so as to maintain children's attention, after each sentence in each Set, there was a comprehension statement to which children were required to make a "TRUE" or "FALSE" response. An example of a target sentence along with its corresponding comprehension sentence for each of the two Sets is shown in Table 4 below.

Trials in each set were always presented in the following order: 20 Practice trials then Test Block 1, Test Block 2, Test Block 3, 18 test trials comprising half spaced and half unspaced sentences. The Practice trials were constructed as follows: 1 spaced warm-up trial, then 9 spaced familiarisation trials, and 1 unspaced warm-up trial, then 9 unspaced familiarisation trials. Within each of the 9 spaced or unspaced trials, there was a range (from low to high) of first and last character frequencies and these were presented randomly. The 18 trials in each of the 3 blocks of test trials were constructed in the same way, 9 spaced and 9 unspaced, and within each 9 variations from high to low of both first and last character frequency.

5.3. 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 participant's left or right eye (depending on which eye was more easily

Table 4
Examples of sentences used in this experiment.

Set 1 (younger children)	
Unspaced sentence	วินมักจะถูกเพื่อนโกรธอยู่เสมอ
Translation	Win's friends always angry at him
Spaced sentence	วิน มักจะ ถูก เพื่อน โกรธ อยู่ เสมอ
Translation	Win's friends always angry at him
Comprehension question	เพื่อนๆ มักจะแกล้งวินอยู่เสมอ
Translation	Win was often *teased* by his friend (FALSE)
Set 2 (older children)	
Unspaced Sentence	นักเรียนใหม่ชือชโลทรมาจากต่างจังหวัด
Translation	Chalothorn is the new student from another province
Spaced sentence	นักเรียน ใหม่ ชือ ชโลทร มาจาก ต่างจังหวัด
Translation	Chalothorn is the new student from another province
Comprehension question	นักเรียนใหม่ชือชโลทร
Translation	New student's name is *Chalothorn*. (True)

tracked in an initial calibration phase, see below). Participants viewed the stimulus sentences on a 21″ NEC CRT monitor with 1024 × 768 pixel resolution and a 60 Hz refresh rate at approximately 50 cm from their eyes. Each sentence was presented stationary in the centre of the screen in Cordia New font size 22. 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.

5.4. Procedure

Each participant was tested individually in a room with minimal noise interference and as minimal light as possible at the Centre for Research in Speech and Language Processing (CRSLP), Chulalongkorn University, Bangkok, Thailand. Before the start of testing and after every break there was a calibration phase in which the participants were required to fixate the centre of each successive calibration dot presented at nine different positions on the screen. These fixation data were then processed in a validation process which determined the degree of accuracy of each participant's fixation at each of the nine positions. Following calibration phase, testing began. Each trial started with a fixation dot located just to the left of where the sentence would be displayed, and once participants fixated this dot display of the stimulus sentence was automatically triggered. Each sentence was presented in the centre of the screen until the child pressed the space bar to indicate they had finished reading, or for a maximum of 30 seconds. After hitting the space bar or 30 seconds of stimulus presentation (whichever came first) the comprehension item for that test sentence was presented. Once the child responded "TRUE" or "FALSE" to the comprehension item (Right Shift for True; Left Shift for False), the next stimulus sentence was automatically presented. Participants were required to respond to the comprehension item before they could move on to the next trial. To guard against child fatigue, for the older children all 4 blocks were presented one after the other, but for the younger children there was always a 5–10 minutes break between Test blocks 1 and 2, and also between Test blocks 2 and 3, if required (see Materials).

5.5. Data analysis

The eye movement data was processed using the DataViewer program (version 1.9.197) to define area of interest (IA) for all words in the sentences and to extract the fixation data of each participant. Then eye movement fixation data of participants were analysed using the *lmer* program for LMM analysis (*lme4*, R package version 1.1–7; Bates, Maechler, Bolker, & Walker, 2014) in the *R* system for statistical computing (*R* Development Core Team, 2006).

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 model used for all analyses comprised a single fixed-effect of spacing (coded as an absent vs present contrast) and age (coded as younger, older, and Adult), the position-specific log frequencies of first and last characters, and word log frequency, each calculated from the 10 million-word CRSLP Thai Language Corpus (Aroonmanakun, Tansiri, & Nittayanuparp, 2009). The random factors included in the model were participant, sentence, and word.

5.6. Hypotheses

Based on results for Thai adults' eye movements (Kasisopa et al., 2013) the following hypotheses were put forward:

(1) The PVL:
   (a) Similar to their adult counterparts (Kasisopa et al., 2013), children's PVL will tend towards the word centre as a product of the relative frequency of word-boundary characters and
   (b) that this will be more evident in older children
(2) Given the greater opacity of last characters (many-to-one grapheme-to-phoneme conversion rules), first character frequency should initially have a stronger effect on viewing times with last character being used increasingly more as a cue as a function of age;
(3) Given that younger children have more recently relinquished reading with spaced text and are less experienced in reading,
   (a) the effect of spacing may well be more powerful than the effect of character frequency especially for the younger children, and
   (b) correspondingly frequencies of the word-boundary characters should have stronger effects in the unspaced condition and that this should be stronger in older than younger children.

6. Results

Responses to the comprehension items were 93% correct for the older children and 88% for the younger children, indicating that the participants understood the sentences well, and maintained attention throughout testing. These comprehension data were not analysed any further. Data for four word-based dependent were collected and these are defined and reported on below.

Landing site: This is the first landing site within each word arising from a right-going saccade in terms of the number of pixels from the word centre. Pixels rather than characters were used as the measurement unit because Thai fonts are proportional rather than fixed width. The mean width of a Thai character in the materials here was 16 pixels and a space, 12 pixels. Word centre was coded as zero pixels, so negative landing site scores are the number of pixels to the left of word centre, and the more negative, the closer the landing site is to word onset.

First fixation: This is the duration in milliseconds of the first fixation within each word arising from a left-to-right saccade;

Single fixation: This is the duration in milliseconds when there is only one fixation on a particular word arising from a right-going saccade. All single fixations are, in fact, first fixations, but all first fixations are not necessarily single fixations

Gaze duration: Gaze duration is the total duration in milliseconds of all fixations within each word including first fixation and all or any subsequent fixations. Gaze duration also encompasses the duration of all refixations and regressions, and so it can be considered (especially when compared with first and single fixations) a measure of the time taken to incorporate information about a word, with shorter gaze durations indicating less processing time.

Each of these four dependent variables were analysed using linear mixed-effects modeling (LMM) involving the factorial manipulations of spacing and age as fixed effects; log frequency of characters in first and last character positions, and overall word frequency as centred covariates, participant, word and sentence as random factors. Due to the low number of observations for longer words the analyses were restricted to 2–6 letter word lengths. In order to allow comparison between spaced and unspaced versions of the same text, we also omitted any fixations on a word that resulted from launches either from the space before a word (in the case of spaced text) or from the last character of the previous word (in the case of unspaced text). Note that degrees of freedom approximations for the t-tests below were calculated using the Satterthwaite (1946) approximation implemented in the R lmerTests package (version 2.0-20).

A summary of data for each of the four dependent variables is given in Table 5.

The model fits for each of the four dependent variables are summarised in Table 6, followed by detailed analyses of these models. 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.

6.1. Landing site analysis

The overall mean landing site for first fixations on a word was to the left of, but very close to, the word centre: −3.5 pixels for younger children and even closer to word centre, −2.55 pixels for older children. The main effect of word frequency was significant (t = 3.712, df = 75, $p < 0.001$). The interaction of first character frequency, spacing, and word frequency was also significant (t = −2.796, df = 361, $p < 0.01$); as can be seen in Fig. 2, the landing site was closer to word centre with higher frequency first characters, an advantage that was particularly pronounced for spaced text and while there was a consistent facilitative effect of high first character frequency, this was potentiated when reading high frequency words. In addition, the interaction between first character frequency x word frequency x saccade length was also found significant (t = 2.936, df = 1716, $p < 0.01$). As can be seen in Fig. 3, the landing site was closer to word centre with higher word frequency, especially with higher first character frequency. The landing site was further to the left of word centre with closer launch distance. Random slopes as well as random intercepts were used in the initial model, but likelihood ratio tests indicated that the random did not significantly increase the likelihood of the model.

6.2. First fixation duration

First character frequency also had an effect on first fixation duration, but only in the context of interactions with age (t = 2.011, df = 1078, $p < 0.05$), with spacing (t = 2.385, df = 278, $p < 0.05$), and with age x spacing (t = -2.643, df = 1231, $p < 0.01$). Fig. 4 shows the nature of these interactions. Older children, quite understandably have generally shorter first fixations and this is so irrespective of spacing or first character frequency. Younger children only show an effect of first character frequency when reading spaced text. Intriguingly, the longest first fixations are by younger children for low frequency first character words in spaced text, even longer than their fixations in unspaced text. As with the landing site data, random slopes as well as random intercepts were used in the initial model, but likelihood ratio tests indicated that the random did not significantly increase the likelihood of the model.

6.3. Single fixation duration

Similar to the results for first fixation duration, first character frequency showed significant interactions with spacing (t = 2.926, df = 295, $p < 0.01$), and age x spacing (t = −2.904, df = 787, $p < 0.05$). As can be seen in Fig. 4 this result is similar to the first fixation results: older children have shorter single fixations irrespective of spacing or first character frequency; and for younger children high first character frequency only promotes shorter single fixations when the text is spaced. The equivalence of the first fixation and single fixation results suggests that the effects of first character, age, and spacing are the same when words require one or more than one fixation, as is often the case with longer words. Random slopes as well as random intercepts were used in the initial model, but likelihood ratio tests indicated that the random did not significantly increase the likelihood of the model.

For single fixation durations the effect of last character frequency also came into play. There was a significant two-way interaction of last character frequency with age (t = −2.488, df = 612, $p < 0.05$), and of age with word frequency (t = −2.104, df = 735, $p < 0.05$). The nature of this interaction can be seen in Fig. 5. Older children generally had shorter single fixations than younger children; and in the older children higher last character frequency facilitated shorter fixation times, especially in high frequency words. On the other hand, for younger children there was a clear word frequency effect on single fixation, but no clear effect of last character frequency.

6.4. Gaze duration

There was only one significant main effect for gaze duration: higher frequency words were viewed for shorter durations than lower frequency words (t = −2.577, df = 93, $p < 0.05$). The nature of these effects can be seen in Fig. 6A. Random slopes as well as random intercepts were used in the initial model, but as with similar model variations for the other dependent measures, likelihood ratio tests indicated that the random did not significantly increase the likelihood of the model.

There were also a number of interactions and these are discussed in three groups and graphed in Figs. 6B and 6C. First, there were significant first character frequency interactions: first character frequency x age (t = 3.015, df = 201, $p < 0.01$) and first character frequency x age x spacing (t = −2.230.164,, df = 1422, $p < 0.05$). As can be seen in Fig. 6B, over and above the effect of age, gaze durations were (a) consistently shorter for words with higher first character frequency, irrespective of spacing or age; and (b) tended to be slightly shorter for high first character words in spaced text. This gaze duration advantage for spaced text was unexpectedly reversed for younger children reading low first character frequency words; perhaps the spacing allowed them to process the low frequency first characters and so they then dwelt on and extracted meaning from these words more readily than in unspaced text. (see upper left hand panel of Fig. 6B).

Second, there were further first character interactions: first character frequency x word frequency (t = 2.219, df = 160, $p < 0.05$), and first character frequency x word frequency x spacing (t = −2.141, df = 263, $p < 0.05$). As can be seen in Fig. 6C, over and above the effect of word frequency in which gaze duration is shorter for high frequency words, in low frequency words the effect of high versus low first character frequency was more apparent, especially in spaced text.

Finally, there were significant interactions involving last character frequency: last character frequency x age (t = 2.016, df = 97,

Table 5
Mean landing site location, first fixation duration, single fixation duration and gaze duration on word with different first, last character frequency and spacing condition of Thai children.

		Spaced text				Unspaced text			
First character frequency		High		Low		High		Low	
Last character frequency		High	Low	High	Low	High	Low	High	Low
Landing site (pixels from word-centre)	Younger	−1.4	−9.0	−3.1	−3.9	−2.7	−5.4	−8.0	−7.2
	Older	−0.4	−0.3	−6.1	−5.5	−1.6	−4.4	−1.9	−5.5
First fixation duration (ms.)	Younger	260	276	279	354	261	289	265	249
	Older	223	245	231	238	231	231	229	223
Single fixation duration (ms.)	Younger	264	252	298	296	274	319	291	265
	Older	236	254	233	277	241	237	242	256
Gaze duration (ms.)	Younger	308	523	421	772	353	376	460	429
	Older	242	281	291	309	261	286	271	333

Note: Word centre equals 0 for Landing Site; left of word centre is negative, right of word centre is positive.

$p < 0.05$), last character frequency x spacing (t = 2.145, df = 428, $p < 0.05$), and last character frequency x age x spacing x (t = -4.315, df = 891, $p < 0.001$). As can be seen in Fig. 6B, over and above the facilitative main effects of higher last character frequency and older age in reducing gaze duration, both age and last character advantages are especially evident in spaced text.

6.5. Comparison with adult data

The adults in Kasisopa et al. (2013) were tested on the same materials (Set 2) as the older children here, and so comparison of those adult and these child results is possible. A summary of the overall means of each of the four variables for Thai adults from Kasisopa et al. (2013) are shown in Table 7 and can be directly compared with the Younger and Older children's results in Table 5. A summary of the results of the children's data with reference to the adult data is given below.

6.5.1. Landing site

Children: In young readers, just as with Thai adults, higher first character frequency played important and significant role in guiding eye movements to the word centre, even in normal Thai unspaced text. However, in contrast to adults, this is more apparent in spaced text and is potentiated in higher frequency words.

Adults: On the other hand, in adults but not in children, the facilitative effect of high first character frequency was also fine-tuned and potentiated by high *last* character frequency.

Developmental Implications: It is possible that the effect of both spaces and word frequency are scaffolds that support the first character frequency effects on children's landing site, and that this scaffolding gradually gives way to a more pure character frequency influence in adulthood, which include not only first, but also last character frequency. Moreover, a Bayesian account of saccade targeting may be able to give a better account of this developmental process (e.g., Krüegel & Engbert, 2014).

6.5.2. First fixation duration

Children: Higher first character frequencies also reduce the duration of children's first fixations, although this is only the case in spaced text.

Adults: In adults however, first fixation durations were shorter as a function of last character frequency.

Table 6
Model analyses – significant effects with reference to the figures in which these effects are graphed.

	FIG	β	SE	df	t	Pr(>|t|)
Landing site (pixels from word centre)						
Intercept		−3.711e+00	1.048e + 00	2.635e + 02	−3.540	0.001***
Log word freq.	2	1.340e+00	3.610e−01	7.490e + 01	3.712	0.000***
Log first character freq. x spacing x log word freq.	2	−1.484e+00	5.308e−01	3.611e + 02	−2.796	0.005**
Log first character freq. x log word freq. x saccade length	2	8.530e−03	2.906e−03	1.716e + 03	2.936	0.003**
First fixation duration (ms)						
Intercept		236	12.403	28.50	19.023	<2e−16***
Log first character freq. x age	3	16.397	8.152	1077.90	2.011	0.045*
Log first character freq. x spacing	3	21.109	8.851	278.00	2.385	0.018*
Log first character freq. x age x spacing	3	−27.203	10.291	1231.40	−2.643	0.008**
Single fixation duration (ms)						
Intercept		252	15.912	45.70	15.850	<2e−16***
Log first character freq. x spacing	3	46.604	15.928	294.60	2.926	0.004**
Log first character freq. x spacing x age	3	−57.617	19.842	787.40	−2.904	0.004**
Log last character freq. x age	4	−46.633	18.741	611.60	−2.488	0.013*
Log last character freq. x age x log word freq.	4	−16.418	7.803	735.20	−2.104	0.036*
Gaze duration (ms)						
Intercept		297	23.328	25.80	12.714	1.32e−12***
Log word freq.	5A	−21.803	8.460	93.00	−2.577	0.012*
Log first character freq. x age	5B	42.116	13.969	201.00	3.015	0.003**
Log first character freq. x age x spacing	5B	−38.276	17.162	1422.40	−2.230	0.026*
Log first character freq. x log word freq.	5C	16.889	7.612	160.40	2.219	0.028*
Log first character freq. x spacing x log word freq.	5C	−20.936	9.665	263.00	−2.141	0.033*
Log last character freq. x age	5D	38.759	19.227	96.80	2.016	0.047*
Log last character freq. x spacing	5D	43.221	20.146	427.50	2.145	0.033*
Log last character freq. x age x spacing	5D	−79.977	18.535	890.90	−4.315	1.77e−05***

Note: FIG. stands for Figure; freq. stands for frequency; '***' significant value of 0.001, '**'0.01, and '*' 0.05.

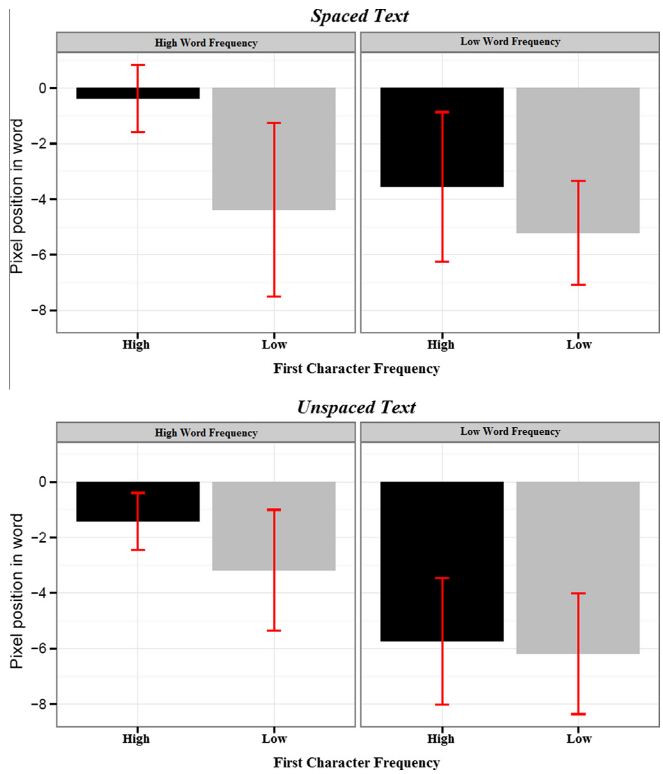

Fig. 2. Landing site variation (and standard errors) on words as a function of first character frequency, overall word frequency, and spacing. The landing site position is measured in pixels and is relative to the word centre. Negative numbers indicate landings closer to the word beginning. Character frequency is dichotomised around the mean.

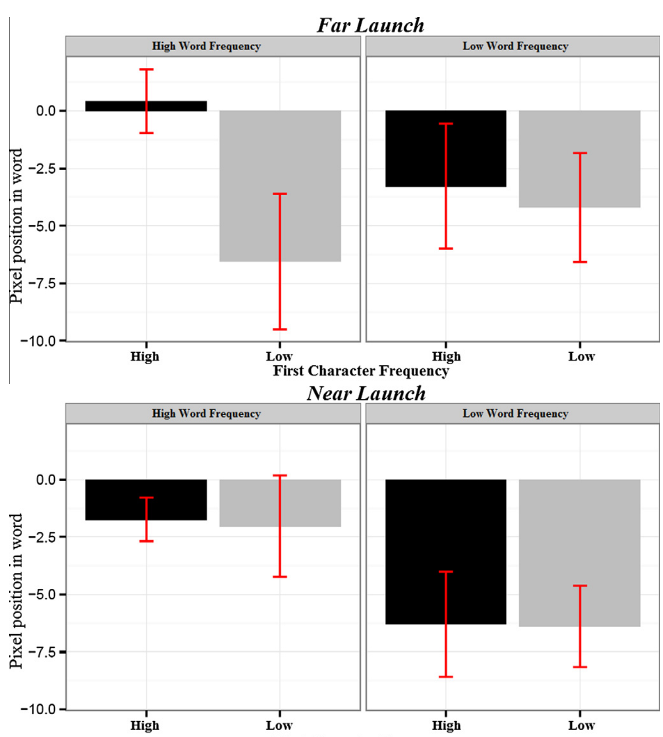

Fig. 3. Landing site variation (and standard errors) on words as a function of first character frequency, overall word frequency, and launch distance. Character frequency is dichotomised around the mean.

Developmental implications: This suggests that first character frequency plays a developmental role in assisting children to recognise and process words more quickly, but only when the first characters can be clearly perceived – in spaced text.

6.5.3. Single fixation duration

Children: First character frequencies also played a significant role for single fixation duration, but in addition, for older children last character frequency facilitated shorter fixation times, especially in high frequency words. In contrast, for younger children there was a clear word frequency effect on single fixation, but no clear effect of last character frequency.

Adults: In adults both first and last character frequencies played a role in reducing single fixation durations.

Developmental Implications: These results suggest that first character frequency facilitates shorter single fixations across ages, but that last character frequency is a word segmentation cue that is picked up in the developing reader *after* the first character frequency cue, and sometime between Grade 7 and adulthood children learn to integrate first and last character cues in processing words.

6.5.4. Gaze duration

Children: Gaze duration is shorter in older children suggesting faster processing by older children, presumably due to greater experience in reading and/or level of cognitive or literacy development. There is also, for both ages faster processing of higher frequency words and faster processing when there are higher frequency last characters. Spacing generally allowed shorter gaze duration but mainly played a moderating and potentiating role; it heightened the higher vs lower first character frequency advantage in younger children; the higher vs lower first character frequency advantage in lower frequency words; and it potentiated the facilitative effect of age on gaze duration and of last-character frequency on gaze duration.

Adults: These results are very similar to those of adults who showed main effects of first character frequency, word frequency, and an interaction of spacing x last character x word frequency.

Developmental Implications: It seems then that as for single fixation, the use of last character frequency may be a cue that is used increasingly strategically as readers mature.

7. Discussion

As predicted in the first hypothesis, the results show that (a) similar to their adult counterparts (Kasisopa et al., 2013), children have a preferred viewing location just left of the word-centre as a product of the relative frequency of word-boundary characters and (b) the older children's landing sites are closer to word centre than are the younger children's, and thus the older children's results are more similar to the adults. The differences between these two groups of children may be due to different reading materials, age, and/or educational achievement of the participants in this study. However, and in accord with the second hypothesis, in both groups, it was only the first and not the last character frequency that affected children's landing site. First character frequency also had facilitative effects on first fixation, single fixation, and gaze duration, and last character frequency did provide some facilitation – on single fixations by the older children, and on gaze duration, but only when text was spaced. Spacing generally played a potentiating role; it potentiated the effect of first character frequency on the PVL in the landing site results, it enabled first character frequency effects on first fixation, and it potentiated the effect of last character frequency on gaze duration. However, in contrast to what was expected from hypothesis three, it is *not*

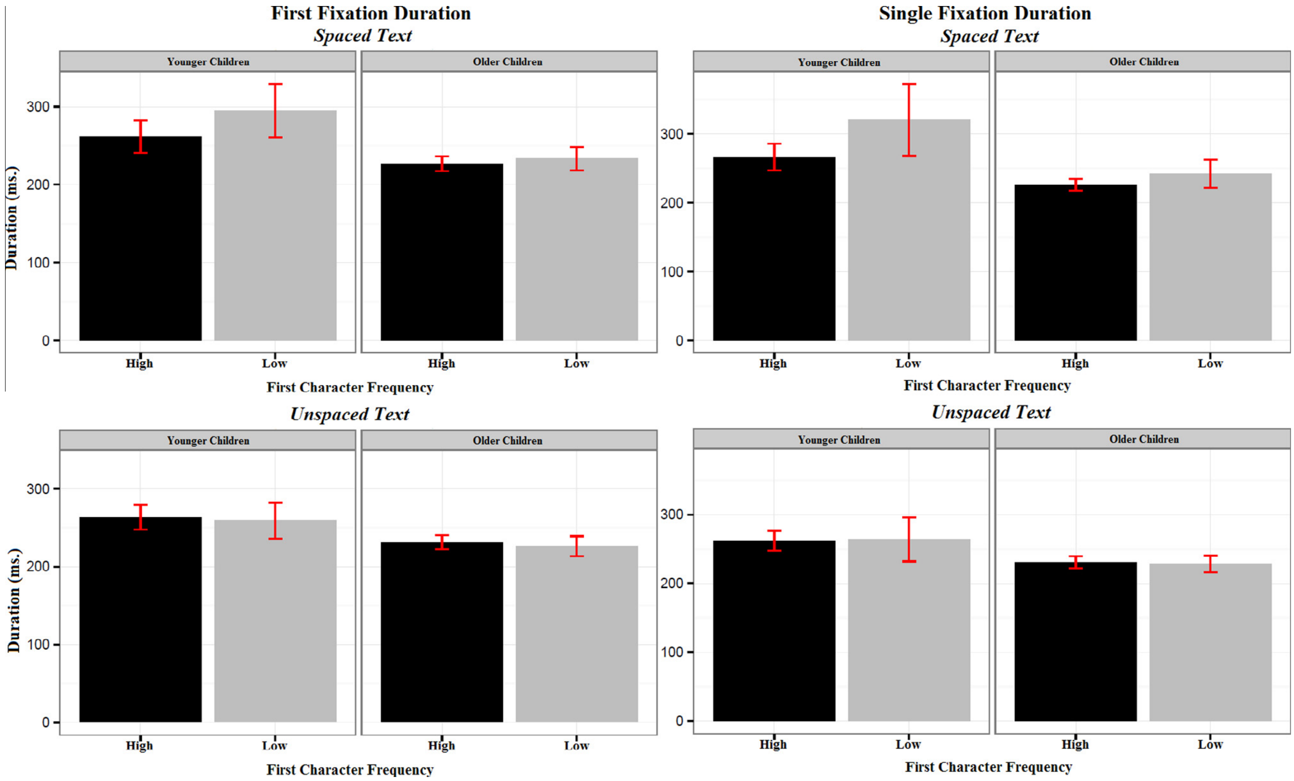

Fig. 4. First fixation and single fixation (first pass viewing time involving just a single fixation) durations in milliseconds (and standard errors) as a function of first character frequency, age, and spacing. Character frequency is dichotomised around the mean.

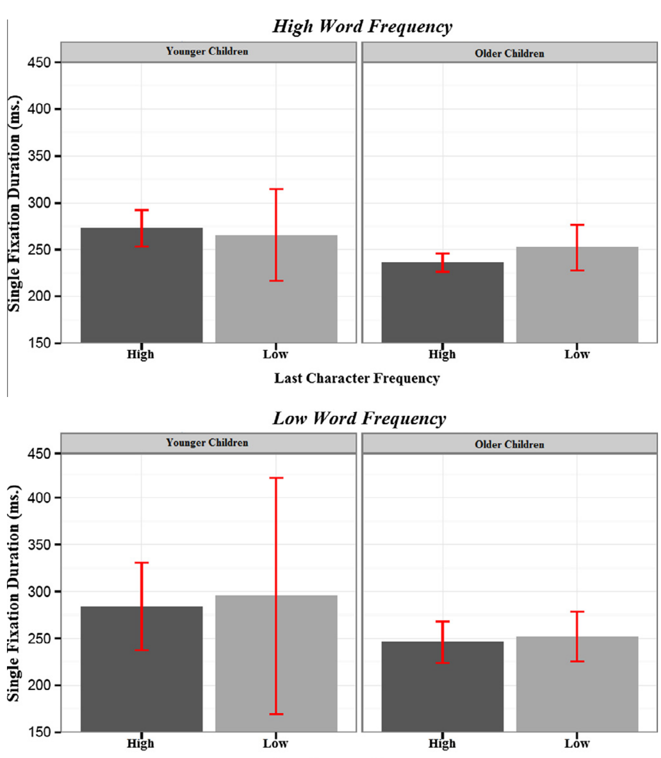

Fig. 5. Single fixation durations in milliseconds (and standard errors) as a function of last character, overall word frequency, and age. Character and word frequency are dichotomised around their respective means.

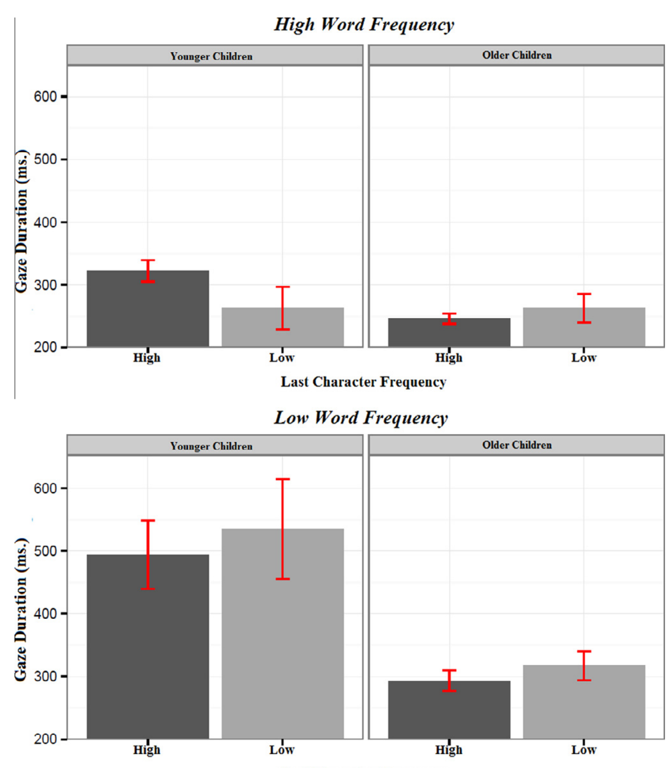

Fig. 6A. Gaze durations (total of first pass fixations on a word) in milliseconds as a function of last character frequency, overall word frequency, and age (and standard errors). Character and word frequency are dichotomised around their respective means.

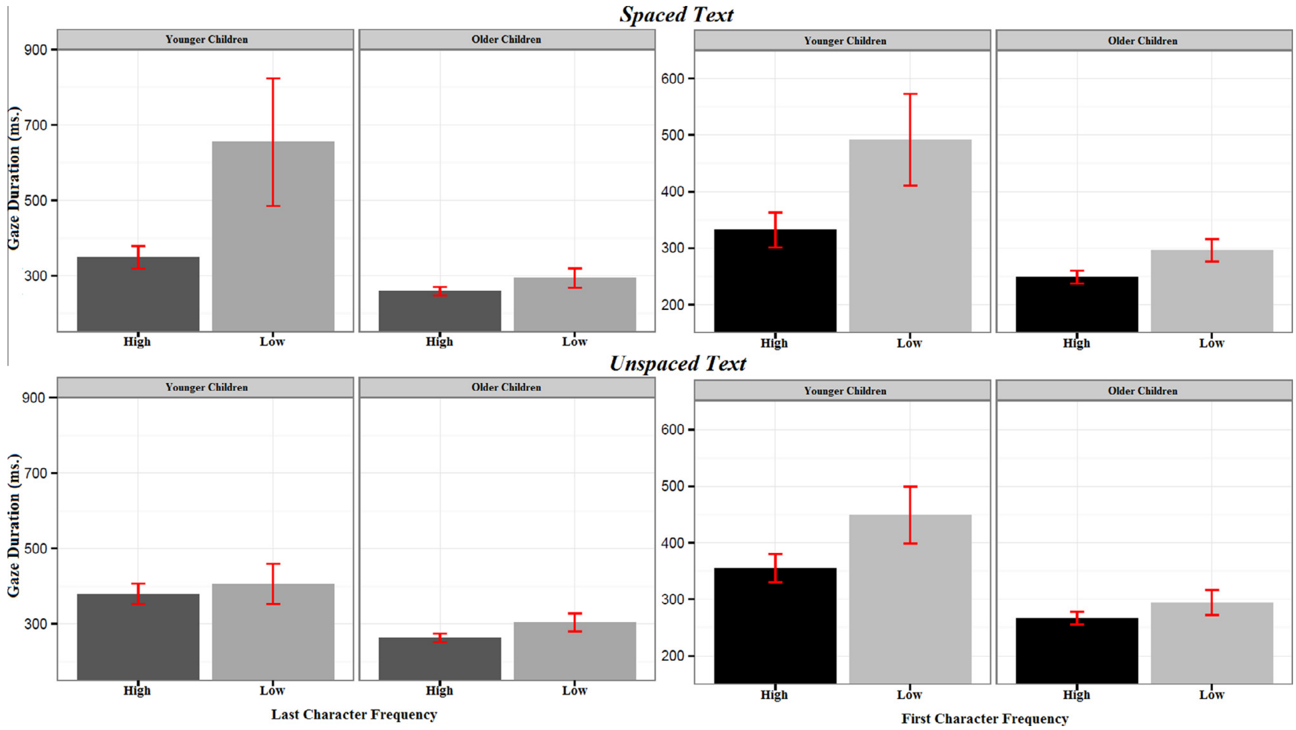

Fig. 6B. Gaze durations in milliseconds (and standard errors) as a function of first character frequency (right panels), last character frequency (left panels), age, and spacing. Character frequency is dichotomised around the mean.

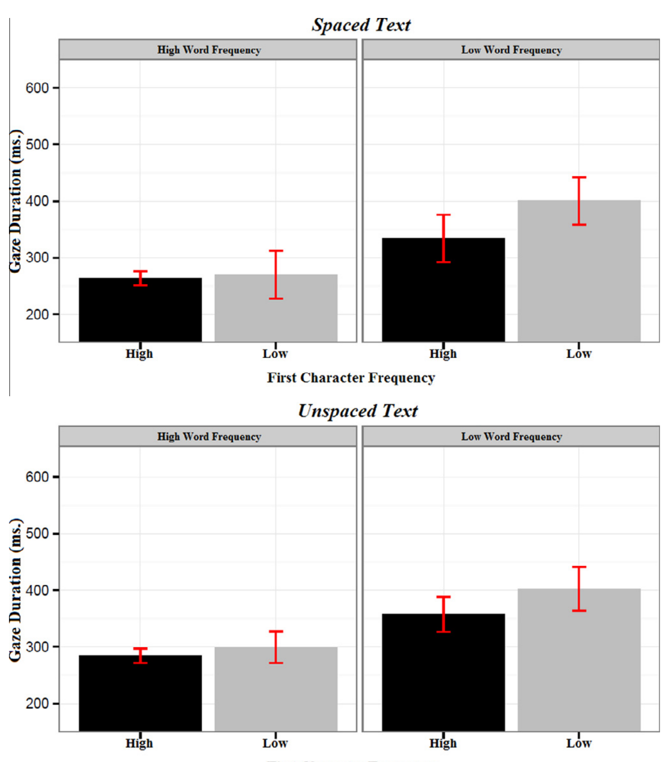

Fig. 6C. Gaze durations in milliseconds (and standard errors) as a function of first character frequency, overall word frequency, and spacing. Character and word frequency are dichotomised around their respective means.

that case that (a) for children, especially the younger ones, spacing has a more powerful on eye movements than does the effects of character frequency especially for the younger children, and (b) that boundary characters affect eye movements and fixation patterns only when children are forced to use these cues, i.e., in the absence of spaces. Rather it appears that spaces potentiate children's in learning to use boundary character frequency effects to aid word segmentation.

The results of this study support the findings by Reilly et al. (2005) and Kasisopa et al. (2013) that the effective saccade target for Thai readers is the word-centre, with the mean landing site for first rightward incoming saccades just left of centre. Moreover, the results here show that this is the case even for Thai children; characters that are diagnostic of word boundaries to help children to target word centres effectively. The presence of high frequency first characters serves to push the landing site further into the word and also tends to shorten viewing times (first character for first fixation, and both first and last character for single fixation and gaze duration.). This means that Thai readers learn to use position-specific relative frequency of character in the first and last positions efficiently in guiding their eye movements from a young age. The fact that this study also showed a significant interaction of overall word frequency with landing site, single fixation and gaze duration suggests that both global word features and boundary characters come into play in reading Thai. A comparison of the children's results here and the adults' results (Kasisopa et al., 2013) allow us to build a relatively comprehensive account of the development of eye movements and fixation patterns in Thai readers. At least by Grade 6 children are able to use first character frequency to guide eye movements to a PVL similar to their adult counterparts and also similar to their counterparts reading spaced scripts. The use of this cue is most evident when there are spaces between words and with higher word frequency. Similarly, first character frequency assists in lowering first fixation duration and spaces help in this. First character frequency also assists single fixations and last character also plays a role and is facilitated by higher word frequency. Last character frequency also facilitates lower gaze durations and spacing facilitates this. So it can be

Table 7
Mean landing site location, first fixation duration, single fixation duration and gaze duration on word with different first, last character frequency and spacing condition of Thai adults.

	Spaced text				Unspaced text			
First Character Frequency	High		Low		High		Low	
Last Character Frequency	High	Low	High	Low	High	Low	High	Low
Landing site (pixels from word-centre)	−0.1	−2.1	−4.2	−4.0	−0.8	−3.9	−3.8	−3.9
First fixation Duration (ms.)	207	225	223	227	217	218	219	240
Single fixation duration (ms.)	209	228	225	227	216	220	219	238
Gaze duration (ms.)	216	253	270	280	233	251	260	328

Note: Word centre equals 0 for Landing Site; left of word centre is negative, right of word centre positive.

concluded that children use first character frequency early in reading Thai and this is scaffolded by spacing and word frequency. Last character frequency appears to be a later development, and again its use is scaffolded by spacing and word frequency.

The increased use of last character frequency over age from 6th to 7th Grade to adulthood may well be a result of the complexity of grapheme-to-phoneme of the last characters in Thai. As the reading skills of the readers increase the ability to use the complex grapheme-to-phoneme mapping rules of the last characters also increases. By adulthood Thai readers are using first and last character frequencies to guide eye movements to the PVL and optimise viewing patterns.

Comparing these results with those of readers of spaced scripts, it appears that the position of the PVL appears to be relatively consistent across alphabetic languages, despite such gross differences as whether there are spaces between words or not. More generally, it appears that in the absence of spacing between words (and even if there *is* spacing between words) experienced readers of a *scriptio continua* script use the relative frequency of boundary characters as cues for word beginning and ending to guide saccades and allocate fixation time resources. It remains to be seen how this skill might develop in younger readers of Thai. In addition, given that Thai children use character frequency to guide eye movements *even when* spaces are provided between words opens the possibility that readers of spaced scripts might also use character frequency to guide eye movements but that this is (a) less powerful than spaces, and (b) has not been detected in spaced text reading as it has not been included as a factor in extant studies.

This study provides evidence that young Thai readers use first character frequency to land their eyes at the PVL and use first and last character frequencies to optimise viewing patterns with both of these scaffolded to varying degrees by word frequency and spaces between words. As only relatively older children were tested here (at the end of primary: 6th Grade, and at the start of secondary: 7th Grade) it will be of interest to investigate the relative roles and the interplay of spacing and boundary character frequency on eye movements and fixation patterns in much younger children. This is now possible using head-free, tracking systems. A longitudinal study is now in progress with Thai children testing them first when they are in Grade 1 (where they are taught to read with spaces) and following them through the transition from spaced text in Grade 1 to unspaced text in Grade 2 and beyond. Such investigations will elucidate whether and what developmental role first character frequency in conjunction with word spacing plays in reading development, and the age at which last character frequency also begins to be used as a cue.

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