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Short title :

Linguistic processes modulate where the eyes move regardless of word boundaries

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Abstract

In most models of eye-movement control during reading, it is assumed that readers move their eyes in a word-based manner along the lines of text. According to this assumption, saccades are invariably guided towards the center of peripheral target words, as selected based on the needs of ongoing (word-identification) processing, and the variability in within-word landing positions exclusively results from systematic and random errors. Here we put this general hypothesis to a strong test by investigating the respective influences of language-related variables (word frequency and word predictability) and lower-level visuo-motor factors (word length and saccadic launch-site distance to the beginning of words) on both word-skipping likelihood and within-word landing positions. To this end, we fitted (generalized) linear mixed-effects models to the eye-movement data of forty participants reading 316 pairs of sentences; each pair differed only by one word, the prime, which was either semantically related or unrelated to a following test word of variable frequency and length. We found that low-level visuo-motor variables largely predominated in determining which word would be fixated next, and where in a word the eye would land. In comparison, language-related variables only had tiny influences. Yet, they affected both the likelihood of word skipping and within-word initial landing positions, all depending on the word's length, or how far on average the eye landed from the word boundaries, and pending the word could benefit from peripheral preview. These findings provide a strong case against the predominant word-based account of eye-movement control during reading, by showing that saccades are primarily guided by low-level visuo-motor processes, regardless of word boundaries, while being overall subject to subtle, one-off, language-based modulations. Our results also suggest that overall distributions of saccades' landing positions, instead of truncated within-word landing-site distributions, should be used for a better understanding of eye-movement control during reading.

Introduction

Reading is a complex perceptual and cognitive task, that not only involves the identification of individual words and their integration in the sentences' syntactic and semantic context, but also requires the execution of saccadic eye movements along the lines of text. Necessitated by the strong decrease of visual acuity with retinal eccentricity, saccades play a crucial role in that they determine which letters and words benefit from detailed viewing on successive eye fixations. Yet, whether they are in turn cognitively guided towards the center of target words (or target word-objects), as selected based on the needs of ongoing word-identification processing, still remains an open question. This is a long-standing assumption, that accounts for a number of well-established eye-movement phenomena [e.g., 1, 2, see also 3, 4]. Nevertheless, due to the slowness of both language-related processes and top-down, word-object-based, guidance, the possibility remains that saccades may primarily reflect low-level visual and oculomotor processes, that would drive the eyes along the lines of text regardless of word boundaries [5-8]. Here we further challenged the word-based view by testing one of its strong predictions: that linguistic factors should exclusively influence the likelihood a word is fixated (vs. skipped), and not where in a word the eyes land, rather than overall modulating saccade amplitudes regardless of word boundaries.

The hypothesis that eye movements during reading are guided in a word-based manner was originally proposed towards the mid-seventies [e.g., 9], and it has since then been a predominant assumption, being expressed in different variants, depending on the level of processing associated with selection of the saccade target word [e.g., 10-13]. It remains today a central assumption, that is implemented in the great majority of models of eye-movement control during reading [1-4, see also 14-16, but see 17]. Although word-based models differ in several important ways, most rely on the same three basic principles, as originally proposed by McConkie et al. [18]: (1) On every eye fixation, a word(-object) is designated as the next-saccade target; (2) The functional target location is the center of the word, to optimize subsequent visual-information uptake and word identification [19; for a review see 20]; (3) Where the eyes land results from a compromise between this word-center targeting strategy and both systematic saccadic range error (SRE; 21, 22, but see 23, 24], a bias to move the eyes a constant, optimal, distance forward [see also 25], and random error. Word-based models also share the assumption that selection of the saccade target word depends on the (estimated) efficiency of letter-extraction and/or word-identification processes, weighted by visual acuity. Where the models differ is in the processing stages that enable this selection.

In E-Z Reader, words are identified sequentially based on successive attention shifts [2]. The target word is by default the next word (N+1) on the line of text, and a saccade to that word starts being programmed as soon as the fixated word (N) has reached a preliminary stage of word processing, referred to as word-familiarity check. When Word N is identified, attention then also shifts towards Word N+1, and this word is processed in peripheral vision until the saccade is ready to go. However, if Word N+1 is processed fast enough (i.e., its word-familiarity check is complete before the saccade program enters a non-labile stage), Word N+2 becomes the saccade target, and Word N+1 is skipped. In SWIFT and GLENMORE, words are processed in parallel within the perceptual span [1, 4]. The target corresponds to the word whose processing-based "saliency" is the highest by the time a random saccade timer, or the level of fixation activity, possibly combined with language-related inhibition, enables the programming of a saccade. The selected word thus depends on the amount of lexical processing achieved on foveal and peripheral words by the time a saccade is ready to go. However, for early-triggered saccades, as additionally proposed in GLENMORE, it is purely determined based on letter visibility (or saliency); the word-object with the highest letter-based saliency becomes the target of the next saccade. Finally, in SERIF, the saccade target is a blob; it is determined in a probabilistic manner, based on the chances of identifying the words within the right/forward perceptual span, as inferred from the words' length and eccentricity, as well as their frequency in the language [3]. Note that the word-center-targeting hypothesis is a bit relaxed in this model, as the saccade target would be shifted towards the beginning of the target word when Word N is associated with high uncertainty.

Regardless of the processing stages involved, these models all predict, in line with previous findings, that words are less likely to be selected for fixation, and hence more likely to be skipped, when they are shorter [e.g., 9], and/or nearer to the saccade's starting location (or launch site [26, 27]), thus when they benefit from peripheral preview [see also 28], as well as when they are more frequent in the language [e.g., 29, 30]. Both E-Z reader and SWIFT additionally predict that words that can be more easily predicted from the sentence's context are also more frequently skipped [e.g., 31, 32, for reviews see 11, 26, 33, 34]. Moreover, word-based models may be able to account for the additional finding that word skipping rate is more greatly affected by word frequency and word predictability, when saccades are launched from closer to the words' beginning [35, 36].

Still, E-Z reader and SWIFT, that exclusively rely on ongoing word-identification processing for selection of a saccade-target word, cannot account, at least without further assumptions [see 37, 38], for the fact that skipping rate also decreases with increasing string length and launch-site distance during the reading of meaningless, z-transformed, text material, thus in the absence of linguistic content [37, 39, 40, see also 41]. Moreover, it remains uncertain how word-based models in general would cope with the likely greater variations in word-skipping rate with word length, compared to word frequency or word predictability, as reported in two meta-analyses [26, 33, see also 42], and as further suggested by comparison of z-reading and normal-reading data [37, 39, 40]. Indeed, since word length is negatively correlated with word frequency, the models' predicted effect of word length across words of different frequencies could simply be an effect of word frequency [see also 43]. This may be particularly the case in E-Z reader and SWIFT, that provide a single explanation for the effects of visual and linguistic variables on word-skipping behavior, despite making the assumption that word skipping may in a few instances occur as a result of SRE (see below).

Word-based models make yet another prediction, that may provide a stronger test of their validity. As they rely on the general hypothesis that saccades invariably aim for the center of selected target words, with systematic and random errors being the only source of variability, they predict that initial eye landing positions in words should largely remain unaffected by the words' linguistic properties. Due to SRE, within-word landing-position distributions should progressively shift towards the very-end of words as saccades are launched from closer to the words' beginning, in line with the well-established launch-site effect [18, 44]. However, they should not be affected by the easiness of peripheral word processing, except maybe in the very rare instances when a word, intended to be skipped, would end up being fixated due to systematic and/or random errors. Still, such mislocated fixations, that would most likely occur when the saccade is launched from very close to the word's beginning and/or the word is short, would mainly lay towards the very-end of words [see 45, 46]. This implies that only the tail of landing-site distributions could possibly diverge between easy and difficult words.

In contrast, the assumption that saccades are primarily guided by bottom-up visuo-motor processes, regardless of word boundaries, would predict overall modulations of saccade amplitude with language-related variables [5, 6, 47, but see 7, 8]. According to this non-word-based view, a word's linguistic properties could thus potentially influence not only the likelihood the word is skipped, but also where in the word the eyes land. These effects should yet remain very small, given the poor resolution in peripheral vision combined with the slowness of language-related processes [48, 49]. However, while in theory language-related variations in word-skipping rate and within-word landing positions should both become greater as more letters from the word fall within the perceptual span (and the words are more efficiently processed), they should still vary differently with word length and/or launch-site distance. This is illustrated in Fig 1, where we represented a hypothetical overall shift of landing-site distributions towards the end of easy words, in comparison with difficult words, for different word lengths and saccades' launch-site distances to the beginning of words; the implemented shift was slightly greater for shorter (left panels) and less eccentric words (upper panels) to reflect the fact that these words more greatly benefit from peripheral preview. This figure suggests that significant effects of word difficulty could potentially be observed on within-word landing positions, but less likely on word-skipping rate, when the distributions happen to peak near the center of words, thus when the launch-site distance is sufficiently large and/or words are long enough for the processing-related shift in landing-site distributions to take place within the word boundaries (see left lower panel and all three right panels). Since these are not all optimal conditions for peripheral word processing, these effects would yet remain rather small, and potentially difficult to observe. In contrast, when the distributions peak near the end of words or even beyond it, as in the case of shorter and less eccentric words (which are also more easily processed), the shift would most often occur outside the word boundaries, and likely result in a significant effect of word difficulty on the likelihood of word skipping, but not on within-word landing positions (see left upper and middle panels). Thus, in this specific case, the non-word-based assumption would meet the predictions of word-based models, but for different reasons. Subsequently, the case of interest, that should help disentangling both views, corresponds to when landing-site distributions happen to peak near the center of the words, given word length and launch-site distance.

Fig1. Illustration of the predictions made by the non-word-based assumption.

Under this assumption, saccade amplitudes should be overall modulated by word-processing difficulties regardless of word boundaries, but to greater extents for shorter and less eccentric words, that more greatly benefit from peripheral preview. Are represented the hypothetical frequency distributions of saccades' landing positions on the line of text for easy (plain lines) vs. difficult (dotted lines) peripheral words (N+1) separately for short and long words (left and right panels) and close, intermediate, and far saccades' launch sites relative to the beginning of the words (from upper to lower panels). Light-grey rectangle areas represent the horizontal extent of the words. Landing positions falling within those areas correspond to within-word landing positions, while landing positions to the right of these areas result in word skipping.

At present, there is no unambiguous evidence for either word-based or non-word-based predictions on within-word landing positions. Studies that manipulated the words' visibility in peripheral vision all failed to reveal a peripheral-preview effect [24, 50, 51]. Furthermore, several studies found no variations in within-word initial landing positions with the frequency and/or the predictability of words [52-54]. Yet, some studies, but not all, did report small, though significant, effects of word predictability on within-word landing positions, when the saccades' launch-site distance to the beginning of words was also taken into account. In two experiments, Lavigne, Vitu and d'Ydewalle [55] presented prime-target word pairs within isolated sentences, with the two words being either semantically related or unrelated. They observed, in accordance with the non-word-based view, an overall slight shift of within-word landing-position distributions towards the end of predictable words, in comparison with non-predictable words, that held only for high-frequency target words of 6-8 letters, in intermediate launch-site conditions (>= -7 letters from the words' beginning).

McDonald and Shillcock [56] used forward transitional probability to investigate whether within-word landing positions vary with the predictability of a word given the immediately preceding word in a sentence. They observed that the eyes landed slightly further into predictable, compared to non-predictable, words of 4 to 7 letters, regardless of launch-site distance (within 1-11 letters from the beginning of the word). However, Rayner et al. [36] failed to replicate these findings, showing no significant effect of frequency and predictability, despite controlling for the saccades' launch site [see also 57, 58]. In fact, there was only a hint of an effect of predictability towards the very-end of landing-site distributions for 5- and 6-letter words in close launch-site conditions (>= -4 letters from the beginning of words). Still, there was a significant effect of predictability on the likelihood of word skipping for the same range of launch-site distances, thus in line with predictions from both word-based and non-word-based hypotheses.

The problem with previous studies is that they were not optimally designed to provide a strong test of the above, word-based and non-word-based, predictions. The number of items per frequency and/or predictability classes was relatively low, and hence made it difficult to further split the data by word length and launch site. Moreover, the discretization of the independent variables, for the needs of the analyses (ANOVAS), was probably not optimal to capture likely subtle and complex trends. The present study overcame these limitations by re-investigating the relative influence of word frequency, word predictability, word length and saccadic launch-site distance on both within-word initial landing sites and word-skipping rate, using (generalized) linear-mixed-effect modeling applied to a large corpus of eye-movement data. This, referred from now on to as the “French-sentence corpus”, was collected while 40 adult participants each read a total of 316 sentences. As in Lavigne et al.'s [55] original study, word predictability was manipulated by using pairs of sentences, that were strictly identical, except for the prime word that was either semantically related or unrelated to a subsequent test word (originally referred to as target word), making a total of 632 sentences. The semantic relatedness between prime and test words was estimated based on the association strength between the two words, as measured in free production norms; the predictability of the test words in the sentences was further assessed using a cloze task. Across sentences, the test word was of variable frequency and length.

Both word-based and non-word-based hypotheses predicted that the likelihood of skipping the test words would vary with their frequency and predictability, though more greatly for shorter and less eccentric words, and hence when visual, lexical and semantic peripheral-word information would get together for a faster access to the word's representation. However, while word-based models predicted that within-word initial landing positions should not be significantly affected by the words' frequency and predictability, the non-word-based view predicted frequency and predictability effects, but mainly for longer words, and/or intermediate launch-site distances (see Fig 1). Moreover, only the latter did unambiguously predict that language-related variations in both word-skipping rate and within-word landing positions would remain much smaller than the effects of word length and saccadic launch-site distance.

Materials and Methods

Participants

Forty ***s***tudents (between 20 and 30 years old) from Aix-Marseille University were paid 15€ to participate in the experiment. All were native speakers of French, and had normal and uncorrected vision. None was aware of the goal of the experiment. Participants gave their informed consent prior to their participation in the experiment. This was conducted in accordance with the ethical standards laid down in the Declaration of Helsinki, and it was approved by the committee responsible for overseeing research conducted in human subjects at Aix-Marseille University.

Materials

A total of 316 pairs of sentences, each containing both a prime and a test word, were constructed, with the prime word appearing first, at the second position in the sentences, and the test word appearing on average 2.8 words later, though never being last, or preceded or followed by punctuation. The two sentences of a given pair were matched except for the prime word which was either semantically related or unrelated to the test word. In each pair, related and unrelated primes were matched in length up to a two-letter difference.

Related prime and test words were selected from available free word-production norms in French [59, 60]; for these, participants were asked to produce the first (test) word (e.g., 'volcano') that came to their mind when reading a given (prime) word (e.g., 'lava'). The computed association strength between the two words corresponded to the proportion of participants producing the test word given the prime. For the 316 related word pairs that were selected for the sentences, the test word was related to the prime with a strength greater than 0.01 (M = 0.36, SD = 0.20; range from 0.01 to 0.91). For the 316 corresponding control sentences, using the same test words but a different prime, the association strength between prime and test words was 0.

To control for the predictability of the test words in the sentences' context, and hence not only relative to the prime, a preliminary study was conducted using a cloze task. In this study, a total of 92 participants (all French-native speakers) were asked to indicate which word first came to their mind when reading the beginning of each of the 632 sentences (up to the word before the test word). This allowed us to calculate the proportion of participants producing the test word in each sentence. In sentences containing related word pairs, and hence predictable sentences, the test word was given by 22-100% of the participants (*M* = 0.66, SD = 0.23), while it was given by 0-4% of the participants (*M* = 0,005, *SD* = 0.013) in corresponding unrelated-word-pair (or unpredictable) sentences (see examples *a* and *b*).

a. La *lave* s'échappe du *volcan* en éruption (predictability = 0.83)

Lava is escaping from a *volcano* in eruption

b. La *fumée* s'échappe du *volcan* en éruption (predictability = 0.00)

Smoke is escaping from a *volcano* in eruption

All selected test words were between 2 and 13 letters long (*M* = 6.05 letters, *SD* = 1.97 letters), and had a frequency between 0 and 1,289 occurrences per million (*M* = 59.31, *SD* = 129.98, according to the variable "Freqlvr" in lexique.org [61]). More details on the distribution of word lengths, word frequencies, and word predictabilities across test words is given in Table 1.

Table 1. Properties of the test words.

WORD LENGTH	N	WORD FREQUENCY				WORD PREDICTABILITY							
						Non-Predictable Sentences				Predictable Sentences			
		Min	Max	M	SD	Min	Max	M	SD	Min	Max	M	SD
2	1	127.23	127.23	127.23	/	0.00	0.00	0.00	/	1.00	1.00	1.00	/
3	20	1.76	315.74	91.58	93.93	0.00	0.04	0.01	0.01	0.26	1.00	0.66	0.24
4	53	0.00	861.49	88.52	164.82	0.00	0.04	0.01	0.01	0.22	1.00	0.62	0.23
5	69	0.14	1289.39	85.07	209.45	0.00	0.04	0.01	0.01	0.22	1.00	0.72	0.23
6	52	0.20	328.78	47.83	63.29	0.00	0.04	0.00	0.01	0.22	1.00	0.68	0.24
7	48	1.22	343.72	52.98	74.82	0.00	0.04	0.00	0.01	0.22	1.00	0.63	0.23
8	41	0.54	73.38	17.18	21.94	0.00	0.04	0.00	0.01	0.22	0.91	0.64	0.20
9	18	0.34	73.38	20.57	22.72	0.00	0.04	0.00	0.01	0.22	1.00	0.69	0.23
10	6	0.74	37.36	13.75	15.52	0.00	0.00	0.00	0.00	0.27	0.96	0.63	0.29
11	5	0.54	15.95	5.11	6.21	0.00	0.04	0.01	0.02	0.30	0.96	0.63	0.26
13	3	0.68	5.68	3.20	2.50	0.00	0.00	0.00	0.00	0.43	0.57	0.51	0.07

From left to right, for each test word length: the number of words, the minimum (Min), maximum (Max), mean (M) and standard deviation (SD) of the words' frequency (in occurrences per million), and the minimum (Min), maximum (Max), mean (M) and standard deviation (SD) of the words' predictability (expressed as a proportion) in non-predictable and predictable sentences respectively.

For the Latin-square design (see below), the 632 sentences were divided into two sub-lists, each containing a total of 316 sentences; half of these sentences were predictable, and the other half were unpredictable, but only one exemplar (predictable or unpredictable) of a sentence pair was present in a given sub-list. The range of word lengths and frequencies was matched as much as possible between the two sub-lists.

Design

Length, frequency and predictability of the test word were manipulated, using a repeated-measure design. Saccades' launch-site distance to the space in front of the test words was defined a posteriori. In the analyses, all four variables were defined as continuous factors (see Data Selection and analyses). Each participant saw only one of the two sub-lists of 316 sentences (see Materials), meaning that he/she saw all test words, but only once, either in the predictable or in the unpredictable condition. However, all 632 sentences were seen across all participants (Latin-square design). For the experiment, each of the two sub-lists was split into six blocks balanced in predictability, frequency and length. The first two blocks contained 60 sentences. The third, fourth, fifth and sixth blocks contained 54, 50, 49 and 43 sentences, respectively. In each block, the order of the sentences was randomized.

Procedure

Upon arrival, the participant was seated comfortably in front of a computer screen, with his/her head movements being minimized with a bite-bar and a frontal head rest. Then, a

15-point calibration phase took place, with the dot appearing successively at 15 positions on the screen (along the two diagonals and above and below the horizontal midline, where the sentence would be further displayed). The participant was asked to first fixate the dot in the upper left corner of the screen, as accurately as possible. When he/she estimated that his/her eyes correctly fixated the dot, he/she pressed a button, which made the point disappear and reappear at the next screen location. The calibration phase was repeated until the correlation between the position of the dot and the estimated eye location was greater than 0.99. A block of trials was then launched.

At the beginning of each trial in a block, the participant was asked to fixate in between two vertically aligned bars presented in the left part of the screen, and centered on the horizontal midline where a sentence would next be displayed. When a fixation was detected within a circular region of 0.5° radius around the bars, the sentence appeared. This remained on screen until the participant indicated through key press that he/she was done with the reading of the sentence. In 20% of the cases, that were distributed randomly within a block, a yes/no comprehension question was then displayed; this was related to the sentence the participant had just read. Participants pressed the right button for a "yes" response, and the left button for a “no” response. After a delay of 2000 ms, the next trial began.

Participants were given a block of 30 practice trials followed by a total of six blocks of test trials. Participants were allowed to take a pause whenever they wanted in between the blocks. Each session lasted approximately 1 hour and 30 min.

Apparatus

Eye movements were recorded using a 5th generation Dual-Purkinje-Image (DPI) Eye-Tracker (Ward Technical Consulting), sampling the right eye position every millisecond with a spatial accuracy of 10 min of arc [62]. The eye tracker was connected through a

National-Instruments (USB 6221 multifunction card) converter to an Intel Xeon dual-core computer running Windows XP. The computer was connected to two screens (one for the experimenter and one for the participant). Custom software was developed with the NI LabVIEW ® 2009 Integrated Development Environment to acquire the eye-movement signal and to analyze it online, while controlling the presentation of the stimuli, contingent on the eye position. The eye-position signal was re-analyzed offline, using the offline saccade/fixation detection algorithm developed by Engbert and Kliegl [63] and implemented in the R software [64] by Laubrock and Kliegl (eyetrackR package; in prep.). Sentences were displayed in white on a black background. They were written in lower cases, except for the first letter of the first word in the sentences as well as the first letter of proper nouns, using the fixed-width *Courier-New* font in PsychoPy. Sentences were saved as separate bitmaps, that were displayed on a gamma-corrected 21" CRT monitor with 85-Hz refresh rate and a screen resolution set to 1280 x 960 pixels. At a distance of 118 cm from the participants' eyes, each character subtended about 0.25 degrees of visual angle. The room was dark except for a dim indirect light source. Vision was binocular.

Data selection and analyses

In the first, main, set of analyses, we measured the likelihood of skipping the test word, as well as the initial eye fixation location in the test word, when this was fixated. We then extended these analyses to all words in the sentences that responded to a number of selection criteria. In both sets of analyses, the fixation of interest was the very first fixation on the space, or beyond the space, in front of a given word (the test word in the main set of analyses). This fixation was selected when (1) it was not preceded or followed by a blink or any signal irregularity, (2) it was within 1° above or below the screen midline where the sentence was displayed, and it was preceded by a fixation also within the vertical margins, (3) it was not the last fixation on the line, and the immediately prior fixation was not the first fixation on the line, (4) it was preceded by a forward saccade, and (5) it corresponded to the very-first fixation on a word. In analyses related to the test word, it was further ensured that the prime word had received at least one fixation before fixation on the test word, or past it (i.e., when the test word was skipped during the first eye pass). In analyses that were not restricted to the test word, additional selections were applied to keep only the words that were neither the first nor the last in a sentence, and that were not preceded or followed by punctuation; compound words were also filtered out.

Within-word landing positions were analyzed by fitting linear mixed-effect (LME) models to the data, using the *lmer* function from the *lme4* package [65] in R [64]. Binary, word-skipping, data were fitted with Generalized LME (GLME) models, using the *glmer* function. The models were implemented after visualizing the data and checking for the linearity of the relationships between the dependent variables and each of the predictors, as well as between the predictors. When linearity failed due to a few extreme factor values associated with a low *n* (e.g., log word frequency <= 0 in word-skipping analyses), these were filtered out to avoid making the model too complex by adding polynomial components, and running the risk in turn that the model would not converge or would give unrealistic estimates. Furthermore, to avoid modeling floor/ceiling effects, further selections were applied to the data. In word-skipping analyses, the words that were either very short or very long and too far out in the periphery were filtered out, as these were associated respectively with one- and zero-skipping probabilities in many participants. In within-word landing position analyses, extreme launch-site values were removed because these were associated mostly with landing positions outside the word boundaries, and hence within-word landing positions that no longer varied with launch-site distance.

In all models, the fixed structure included a linear component for each factor under study (word length, launch-site distance, word frequency, and also word predictability in test-word analyses), and all possible interactions, though never four-way interactions; the latter are indeed difficult to interpret and actually often prevented GLME models to converge. All factors were defined as continuous variables; they were centered on their mean. For the random structure, this comprised a random intercept by participant and by sentence (pair), as well as by-participant random effects of all factors, unless the model failed to converge even after removing the correlation between random effects (which happened more frequently with GLME models). When this was the case, the random intercept by item was removed first, and then, if the model still did not converge, several combinations of random effects were tested until the model converged, but removing first random effects of word length and/or launch site, as these effects are known to be quite robust and to show smaller variations between individuals compared to the effects of linguistic variables.

In the models, word frequency was expressed in log units, as classically done [e.g., 66]. For word predictability, expressed as a proportion, we used, following Kliegl et al. [66], the logit transform; logits were defined as 0.5*ln(predictability/(1-predictability)), but after replacing predictabilities of zero and 1 with 1/(2*92) and (2*92-1)/(2*92) respectively, where 92 represents the number of participants in the cloze task (see Materials). For saccadic launch-site distance, it is classically expressed in letters relative to the center of words, at least in analyses of within-word landing positions [18]. However, since our analyses were aimed at testing the general prediction that frequency and predictability combine with letter visibility in determining where the eye moves, defining launch-site distance relative to the space in front of the words was more appropriate. Indeed, for a given launch-site distance relative to the beginning of a word, but not relative to the center of the word, the number of letters falling within the perceptual span is the same irrespective of the word's length. For illustration purposes only (but not LME analyses), word frequency (in log units), word predictability (in logit units), and launch-site distance (in letters) were categorized in two, three or four bins depending on the needs of the analyses; this was done after splitting the distribution of the corresponding variable in 2-4 equal parts respectively. Note that for word frequency, binning was made separately for different word lengths, given the correlation between word frequency and word length.

The exact number of degrees of freedom for the t-values of fixed effects in LME models remains undetermined. However, given the large number of observations, participants, and items entering our analyses, t-distributions converged to a normal distribution. Therefore, we considered as significant, the effects whose absolute t-value was greater than 2, which corresponds to a significance level of 5% in two-tailed tests [67, 68].

Results

For comparison with previous reading studies, we first analyzed the global characteristics of our participants' eye movements while they were reading the sentences. As typically reported, we found that participants moved their eyes mainly forward, making regressions in about 14.94% of the cases on average [34]. The mean of the medians of progressive- and regressive-saccade lengths were on average of about 8.35 and -4.49 letters, while the mean of the medians of fixation durations were on average of about 241 ms. Words were skipped on average in 52.15% of the cases during a first eye pass, and when they were fixated, they received more than one consecutive fixation in about 11.38% of the cases.

We next tested alternative predictions from word-based and non-word-based accounts of eye guidance during reading. To this end, we analyzed the metrical properties of forward eye-movement behavior in the vicinity of the words (either the test words only or all words in the sentences that responded to our selection criteria –see Materials and Methods), using the likelihood of word skipping and (within-word) initial landing positions as dependent variables. These were analyzed as a function of saccadic launch-site distance to the space in front of the words, word length and word frequency, as well as word predictability in analyses restricted to the test words.

Probability of skipping the test words

In Fig 2, the mean probability of skipping the test words was represented as a function of the words' length, separately for two categories of word frequency and word predictability. This indicates that the likelihood of word skipping largely decreased with increasing word length, but showed very little variation with language-related variables, being only slightly lower for low- compared to high-frequency words of 3-4 and 6 letters, and for low- compared to high-predictability words of 4 letters.

Fig2. Test-word skipping rate by length, frequency and predictability.
Mean probability of skipping the test words as a function of the words' length (in letters), separately for two categories of test-word frequencies (A) and predictabilities (B), as determined after grouping test-word frequencies and predictabilities into two bins respectively (see Materials and Methods).

When data were further split by saccades' launch-site distance to the beginning of the test words, the effects of linguistic variables tended to be clearer and more consistent, despite the lower *n*. This is shown in Fig 3A-B for the case of 4- and 6-letter words. Word-skipping rate was slightly lower for rare compared to more frequent words, as well as for low-compared to high-predictability words of 4 letters at least, though mainly in close launch-site conditions (> -8 letters). Moreover, there was a trend for the effect of word frequency to be slightly greater in high- compared to low-predictability words (Fig 3C-D). Yet, word-skipping rate remained more largely affected by word length and saccadic launch-site distance: as saccades were launched from further away from the beginning of the test words, the likelihood of word skipping decreased drastically, and even more so as words became longer.

Fig3. Test-word skipping rate by launch site, frequency and predictability.
Mean probability of skipping 4- and 6-letter test words as a function of the saccades' launch-site distance to the space in front of the words (binned in two-letter intervals), separately for two categories of test-word frequencies (across word predictabilities; A) and two categories of test-word predictabilities (across word frequencies; B), and for high- vs. low-frequency test words of low- and high-predictability (C and D respectively). The two categories of word frequencies and word predictabilities were determined after grouping test-word frequencies and predictabilities into two bins respectively (see Materials and Methods).

Due to floor and ceiling effects, the respective and combined influences of the four independent variables on word-skipping likelihood could only be estimated over a subset of word lengths and saccadic launch-site distances. Therefore, to estimate the relationship between word skipping rate and word length, and its possible variations with word frequency and word predictability, nearly over the entire range of word lengths, a first GLME model (Model 1) was implemented, with only word length (3-11 letters), word frequency, word predictability, and their interactions, as predictors, thus across all observed saccadic launch-site distances. A second GLME model (Model 2), that comprised word length, launch-site distance, word frequency and word predictability, as well as all possible 3-way interactions, as predictors, was then fitted to a smaller subset of the data, including only word lengths between 4 and 8 letters and saccadic launch-site distances less than or equal to 6 letters from the space in front of the test words.

The fixed effects of Model 1 are presented in Table 2. The intercept estimate (logit: -1.54638), indicates that the test words were skipped in about 17% of the cases when all variables were at their reference (mean) value, and hence when the words were about 6 letters long. Shorter, 3-letter, test words were skipped about twice as often (38%), and longer, 11-letter, test words were skipped much more rarely (3%), as suggested by the significant negative slope estimate for the effect of word length (logit: -0.35200). There was no main effect of word frequency (logit: -0.01747, $p = 0.40$). However, the significant negative slope estimate for the interaction between word frequency and word length (logit: -0.03302) suggested an increase in the effect of word length with increasing word frequency, implying that shorter words (i.e., of about 6 letters ; the reference, mean, value for word length) were skipped more often, and longer words were skipped less often, as they became more frequent.

Table 2. Fixed effects of GLME Model 1 for the probability of skipping the test words.

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-1.54638	0.08271	-18.69599	0.00000
FREQ	-0.01747	0.02103	-0.83075	0.40611
PRED	0.00975	0.01752	0.55643	0.57791
LENGTH	-0.35200	0.02386	-14.75205	0.00000
FREQ:PRED	-0.01060	0.01257	-0.84304	0.39921
FREQ:LENGTH	-0.03302	0.01117	-2.95562	0.00312
PRED:LENGTH	-0.00509	0.01050	-0.48438	0.62812
FREQ:PRED:LENGTH	-0.00218	0.00682	-0.31889	0.74981

Word length (“LENGTH”; 3-11 letters), word frequency (“FREQ”; 0.20-5.93 log units), and word predictability (“PRED”; between -2.60 and 2.60 logit units), as well as all possible interactions, were entered as predictors. The random structure included a random intercept by participant, as well as by-participant random effects of word length, word frequency and word predictability; with a random intercept by sentence pair, the model did not converge. The model's estimates and standard errors are expressed in logit units; they can be back transformed into probabilities, using the inverse logit formula: p = $\exp^{(x)}$ /(1 +$\exp^{(x)}$). The intercept estimate (logit: -1.54638) indicates that the probability of word skipping was of about 0.17 when all variables were at their reference, mean, value (Word Length: 5.96 letters; Word Frequency: 3.03 log units; Predictability: -0.98 logit units). Colon stands for interaction.

As further illustrated in Fig 4A, where the model's predictions were represented for the two most extreme word-frequency values across all selected test words (0.20 vs. 5.93 log units), these variations in skipping rate with word frequency still remained very small in comparison with the effect of word length. The difference in word-skipping rate between the lowest and the highest word frequencies was of a maximum of about 11% in the shortest, 3-letter, test words, and this was yet an overestimation of the actual effect of word frequency, given the smaller range of word frequencies for most word lengths, as well as the variability in word frequencies. Indeed, when the model's estimated word-skipping rate was contrasted for high- vs. low-frequency words on average (or the mean frequency of all test words, when categorized in two frequency bins), as in Fig 4B, the predicted effect was even tinier (see also Fig 2A). None of the other effects or interactions were significant.

Fig4. Estimated effects of visuo-motor and linguistic factors on test-word skipping rate. Probability of skipping the test words, as predicted by GLME Model 1 (A-B; see also Table 2) and GLME Model 2 (C-D; see also Table 3), represented as a function of word length (in letters; A-B), and for 4- and 6-letter test words as a function of saccadic launch-site distance (in letters relative to the space in front of the test words; C-D). In A,C, the models' predictions were contrasted for the two most extreme (i.e., the lowest vs. the highest) word-frequency values across all selected test words regardless of their length and their predictability (0.20 and 5.93 log units respectively), and in D, they were contrasted for the two most extreme (i.e., the lowest vs. the highest) word-predictability values across all test words (-2.6 vs. 2.6 logit units). Note that this led to overestimate the actual effects of linguistic variables, and even more so for the word-frequency effect in words longer than 4 letters, whose frequency range was much smaller. This is illustrated in B, where Model 1's predictions were represented for the mean frequency value of high vs. low-frequency words, as defined after grouping word frequencies into two bins (see Materials and Methods; 2.01 vs. 4.18 log units).

As shown in Table 3, where Model 2's fixed effects were reported, similar though clearer trends were observed when saccades' launch-site distance relative to the space in front of the test words was taken into account. There was again a significant negative slope estimate for the effect of word length (logit: -0.41942), indicating that word-skipping rate decreased with increasing word length. Moreover, the tendency for this effect to become greater in shorter words confirmed, as suggested by the significant interaction between word frequency and word length (logit: -0.05104). There was in addition a significant effect of launch-site distance (logit: 0.54255), indicating that the test words were less frequently skipped as saccades were launched from further away from the words' beginning; this effect was huge as word-skipping rate dropped by as much as 56% for a 6-letter decrease in launch-site distance. Furthermore, the interaction between word frequency, word length, and launch-site distance was significant (logit: 0.02513), and the interaction between word predictability, word length and launch-site distance was marginally significant (logit: 0.01978, $p = 0.08113$). As illustrated in Fig 4C-D, the estimated likelihood of skipping short, 4-letter, words largely varied between the two most extreme word-frequency values across all test words, and to a lesser extent between the two most extreme word-predictability values, at least for saccadic launch-site distances greater than 1-2 letters respectively. In contrast, the difference in skipping rate between the highest and the lowest frequencies/predictabilities for longer, 6-letter, words was smaller, and it decreased with increasing launch-site distance. Still, even in 4-letter test words, the estimated frequency and predictability effects remained much smaller compared to the effect of launch-site distance (4-letter words: 13% and 3% respectively compared to 64%).

Table 3. Fixed effects of GLME Model 2 for the probability of skipping the test words.

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-1.11883	0.13331	-8.39292	0.00000
FREQ	0.00071	0.02943	0.02421	0.98069
PRED	0.00037	0.02703	0.01374	0.98904
LENGTH	-0.41942	0.03043	-13.78204	0.00000
LAUNCH	0.54255	0.02369	22.90694	0.00000
FREQ:PRED	0.02384	0.01771	1.34627	0.17821
FREQ:LENGTH	-0.05104	0.02167	-2.35554	0.01850
PRED:LENGTH	-0.01358	0.01971	-0.68906	0.49079
FREQ:LAUNCH	0.01101	0.01725	0.63851	0.52314
PRED:LAUNCH	0.01568	0.01386	1.13089	0.25810
LENGTH:LAUNCH	0.01082	0.01778	0.60886	0.54262
FREQ:PRED:LENGTH	0.01700	0.01354	1.25550	0.20930
FREQ:PRED:LAUNCH	0.00080	0.01011	0.07867	0.93729
PRED:LENGTH:LAUNCH	0.01978	0.01134	1.74416	0.08113
FREQ:LENGTH:LAUNCH	0.02513	0.01282	1.95955	0.05005

Word length (“LENGTH”; 4-8 letters), word frequency (“FREQ”; 0.20-5.93 log units), word predictability (“PRED”; between -2.60 and 2.60 logit units), and saccadic launch-site distance (“LAUNCH”; between -6.00 and -0.002 letters from the space in front of the test words), as well as all possible two- and three-way interactions, were entered as predictors. The random structure included a random intercept by participant, as well as by-participant random effects of word frequency and word predictability; with a random intercept by sentence pair, as well as random effects of word length and launch-site distance, the model did not converge. The model's estimates and standard errors are expressed in logit units. The intercept estimate (logit: -1.11883) indicates that test words were skipped in about 25% of the cases, when all variables were at their reference, mean, value (Word Length: 5.82 letters; Launch Site: -2.93 letters; Word Frequency: 3.06 log units; Word Predictability: -0.96 logit units). Colon stands for interaction.

In sum, the likelihood of skipping the test words was influenced by the words' length [9] and eccentricity [26, 27], as well as the words' linguistic properties [for a review see 34]. Yet, the effects of word length and saccadic launch-site distance predominated. They were not only greater in size compared to the effects of word frequency and word predictability, but they held nearly over the entire range of word frequencies and predictabilities. In contrast, word-frequency and word-predictability effects intervened only when the words were very short, and/or very close to the saccades' launch site, thus when conditions were met for the words to benefit from peripheral preview. In other words, language-based word-skipping behavior seemed to emerge only when there was strong-enough evidence for the identity of the test word. These findings may be hard to reconcile with the hypothesis, proposed in E-Z Reader and SWIFT models, that eye-movement guidance from one word to the next depends nearly exclusively on ongoing peripheral word-identification processing. They may suggest instead that low-level visuo-motor mechanisms predominate in determining which word is going to be fixated next. The possibility remains that the small contribution of language-related variables was due to the specific (linguistic) properties of our test words, and their restricted range of frequencies in particular. To ensure this was not the case, the same analyses were conducted again, but using this time all words in the sentences that could be possibly analyzed given our selection criteria.

Skipping rate across all words in the sentences

The above analyses were restricted to the test words for the simple reason that test words were best controlled and differed not only in terms of their frequency in the language, but also their predictability from the sentence's context. However, the properties of the test words, and/or their relatively low n (see Table 1), could be responsible for our observation of a rather limited influence of language-related variables on word-skipping rate. Here, we thus replicated the above test-word skipping analyses, but using all words in the sentences, except for the words that did not respond to the above-defined selection criteria (see Materials and Methods). Note though that word predictability was not available for words other than the test words; it was therefore not considered in the present analyses.

As shown in Fig 5, word length and saccadic launch-site distance again predominated in determining the likelihood of word skipping. First, there was a gradual decrease in word-skipping rate with increasing word length, that largely remained unaffected by word frequency; only tiny differences between high- and low-frequency words emerged, and mainly for short, 3- and 4-letter, words (Fig 5A). Moreover, when data were further split by saccadic launch-site distance, separately for different word lengths, an effect of word frequency emerged, in addition to the drastic reduction in word-skipping rate with increasing launch-site distance, but mainly in short words (e.g., 4 letters; see Fig 5B). In longer, 6-letter, words, the effect was already strongly reduced, being visible only in very-near launch-site cases.

Fig5. Word-skipping rate by length, launch site and frequency.

Mean probability of word skipping, across all words in the sentences that responded to our selection criteria, as a function of word length (in letters; A), and for 4- and 6-letter words as a function of saccadic launch-site distance (in letters relative to the space in front of the words;

B), separately for two categories of word frequencies, as determined after grouping word frequencies into two bins (see Materials and Methods).

To further test these trends, two GLME models were fitted to the data, as for the test words. The first, Model 1', tested the contribution of word length and word frequency, as well as their interaction, nearly over the entire range of word lengths (3-11 letters). As shown in Table 4, where the model's fixed effects are reported, the likelihood of word skipping significantly decreased with increasing word length (logit: -0.62141). It also varied with word frequency, though only in interaction with word length (logit: -0.02936): it was greater for higher-frequency words, though gradually less as the words were longer; the main effect of frequency was not significant (logit: 0.02023, $p = 0.18$). In fact, as illustrated in Fig 6A, where the model's predicted relationship between word-skipping rate and word length was represented separately for the two most extreme word-frequency values across all selected words, the word-frequency effect held only for words shorter than about 6 letters. Moreover, as in the above test-word analyses, this effect was much smaller compared to the effect of word length: Word-skipping rate dropped by about 68% for an 8-letter reduction in word length (3-11 letters), while it varied by about 16% at the very most (i.e., for 3-letter words) between the highest and the lowest word frequencies.

Table 4. Fixed effects of GLME Model 1' for the probability of word skipping.

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-0.44797	0.10156	-4.41090	0.00001
FREQ	0.02023	0.01515	1.33509	0.18185
LENGTH	-0.62141	0.02540	-24.46100	0.00000
FREQ:LENGTH	-0.02936	0.00475	-6.17455	0.00000

This analysis was conducted across all words in the sentences that responded to our selection criteria (see Materials and Methods). Word length ("LENGTH"; 3-11 letters) and word frequency (“FREQ”; between 0.01 and 9.59 log units), as well as their interaction, were entered as predictors. The random structure included a random intercept by participant and by sentence, as well as by-participant random effects of word length and word frequency. The model's estimates and standard errors are expressed in logit units. The intercept estimate (logit: -0.44797) indicates that the words were skipped in about 39% of the cases when all variables were at their reference, mean, value (Word Length: 5.05 letters; Word Frequency: 5.56 log units). Colon stands for interaction.

Fig6. Estimated effect of visuo-motor and linguistic factors on word-skipping rate. Probability of word skipping across all words in the sentences, as predicted by GLME Model 1’ (A; see also Table 4) and GLME Model 2’ (B; see also Table 5), represented as a function of word length (A) and for 4- and 6-letter words as a function of saccadic launch-site distance (in letters relative to the space in front of the words; B), separately for the two most extreme (i.e., the lowest vs. the highest) word-frequency values across all words selected for analysis (0.01 and 9.59 log units respectively). Note that this led to largely overestimate the actual word-frequency effect, and even more so when words were longer than 4 letters, as their frequency range was much smaller.

Model 2’ included saccadic launch-site distance (expressed relative to the space in front of the words), and its interaction with word length and/or word frequency, as additional predictors, but for a subset of the data given floor and ceiling effects (word lengths between 4 and 8 letters and launch-site distances less than or equal to 6 letters). As summarized in Table 5, there were again significant effects of word length (logit: -0.69834) and launch-site distance (logit: 0.56677), indicating that the likelihood of word skipping strongly decreased as words became longer and saccades were launched from further away. In addition, there was this time a main effect of word frequency (logit: 0.03827), such that more frequent words were skipped more often. Still, this effect was again greater for shorter words, as suggested by the significant interaction between frequency and length (logit: -0.07564). Moreover, the three-way interaction between word frequency, word length and launch-site distance was significant (logit: 0.01444). This is illustrated in Fig 6B, where the model's predicted relationship between word-skipping probability and launch-site distance was represented for the two most extreme word-frequency values across all selected words, separately for 4- and 6-letter words. As for the test words, there was an effect of word frequency in short 4-letter words, that held over the entire range of tested saccadic launch-site distances (>= -6 letters), but barely no frequency effect in longer, 6-letter, words, except for very-small launch-site distances. This effect, even in 4-letter words where it was the largest, again remained much smaller than the effect of launch-site distance: for a 6-letter increase in launch-site distance, word-skipping rate decreased by about 65%, while it varied by a maximum of about 35% between the highest and the lowest word frequencies. Recall though that this was still an overestimation: given the variability in word frequencies, the actual effect of word frequency was even smaller (see Fig 5B).

Table 5. Fixed effects of GLME Model 2' for the probability of word skipping.

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-0.99019	0.12297	-8.05222	0.00000
FREQ	0.03827	0.01915	1.99834	0.04568
LENGTH	-0.69834	0.03823	-18.26841	0.00000
LAUNCH	0.56677	0.04363	12.99003	0.00000
FREQ:LENGTH	-0.07564	0.00995	-7.60081	0.00000
FREQ:LAUNCH	-0.00084	0.01135	-0.07392	0.94107
LENGTH:LAUNCH	0.03039	0.01932	1.57277	0.11577
FREQ:LENGTH:LAUNCH	0.01444	0.00659	2.18949	0.02856

This analysis was conducted across all words in the sentences that responded to our selection criteria (see Materials and Methods). Word length ("LENGTH"; 4-8 letters), word frequency

(“FREQ”; between 0.01 and 9.02 log units), and saccadic launch-site distance (“LAUNCH”; between -6.00 and -0.002 letters from the space in front of the test words), as well as all possible interactions, were entered as predictors. The random structure included a random intercept as well as random effects of word length, saccadic launch-site distance and word frequency by participant; with a random intercept by sentence, the model did not converge. The model's estimates and standard errors are expressed in logit units. The intercept estimate (logit: -0.99019) indicates that the words were skipped in about 27% of the cases, when all variables were at their reference, mean, value (Word Length: 5.63 letters; Launch Site: -2.48 letters; Word Frequency: 4.34 log units). Colon stands for interaction.

Thus, when all words in the sentences were considered for analysis, the pattern of findings matched that observed in test-word analyses. The likelihood of word skipping was again primarily influenced by word length [9] and saccadic launch-site distance [26, 27]. Word frequency also contributed, but to a much smaller extent compared to visuo-motor variables [see also 26, 33], and mostly when the words could benefit from peripheral view, that is when they were very short or very-near to the saccade’s launch-site. These findings, consistent with both word-based and non-word based accounts of eye-movement guidance, still represent a challenge for models like E-Z Reader and SWIFT, that rely on the assumption that saccades are nearly exclusively guided by ongoing peripheral word-identification processes.

Initial landing positions in the test words

Showing that word-skipping behavior is primarily a function of visuo-motor variables represents a challenge for existing models, and E-Z Reader and SWIFT in particular, as this clearly shows that eye-movement guidance from one word to the next cannot exclusively rely on ongoing word-identification processes. However, it does not necessarily challenge the hypothesis that saccades are guided in a top-down, word-based, manner, towards the center of selected target word-objects. Analyses of within-word landing positions were aimed at directly testing this assumption. These investigated whether the same variables that were found to influence word-skipping rate would also influence where in a word the eye lands, as would be predicted exclusively by a non-word-based account of eye-movement guidance.

In Fig 7A-B, the distributions of initial landing positions in the test words were represented for a subset of word lengths and saccadic launch-site distances, separately for high- vs. low-frequency and high-vs. low-predictability test words, respectively, but across participants. High- and low-frequency categories, as well as high- and low-predictability categories, were defined after grouping words into four bins; they corresponded to the first and the fourth bin respectively (see Materials and Methods). These distributions first revealed a clear launch-site effect, in accordance with McConkie et al.'s [18] original findings: As saccades' launch site laid further to the left of the test words (from upper to lower panels), landing-site distributions shifted accordingly, thus moving from the very-end towards the very-beginning of short words (left two panels), and from a position to the right of the words' center to the words' beginning in the case of long words (right two panels). Also in line with previous findings, landing-site distributions showed very little variations with the frequency or the predictability of the test words. Still, for long, 7- and 8-letter, test words, landing-site distributions tended to peak slightly closer to the words' end with increasing frequency (Fig 7A), and to some extent also with increasing predictability (Fig 7B), though mainly in close launch-site cases (> -6 and -4 letters respectively), thus when the test words could benefit from peripheral preview. This is in accordance with the non-word-based view (see also Fig 1), and opposite to the prediction made by word-based models, that language-related effects on within-word landing positions should only occur towards the tails of the distributions. For shorter, 3- and 4-letter, test words, the major part of the distributions associated with high-frequency words tended to lay underneath that for low-frequency words, at least in close launch-site conditions, thus suggesting also a rightward shift. However, the shift likely took place beyond the word boundaries (not plotted here), thus yielding, in the case of short test words, word-frequency and word-predictability effects on the likelihood of word skipping, as shown above, but not on within-word initial landing sites.

Fig7A / Fig7B. Distributions of initial landing positions in the test words

Across-participants probability density functions (bandwidth: 1 letter or 0.25°; Gaussian Kernel) of initial landing positions in short and long test words (3-4 letters and 7-8 letters in left and right panels respectively), for different saccadic launch-site distances (in letters relative to the space in front of the test words), binned in two-letter intervals (from upper to lower panels: [0,-2[, [-2,-4[, [-4,-6[, [-6,-8[, referred to as -1,-3,-5 and -7 respectively), and separately for the two most extreme categories of word frequencies (A) and of word predictabilities (B), when these were grouped respectively into four bins (see Materials and Methods). Light-grey rectangle areas represent the horizontal extent of the words.

LME modeling of initial landing positions in the test words shed further light on these trends. The model's fixed effects, summarized in Table 6, first revealed that the eye initially fixated a position slightly to the left of the words' center (intercept estimate: -0.55607) when all variables were at their reference, mean, value, and words were about 6 letters long. As further indicated by the negative slope estimate for the effect of word length (slope estimate: -0.20229), this leftward bias increased as the test words became longer [see also 69]. Furthermore, saccades landed closer to the beginning of the test words as they were launched from further away; the slope estimate for the effect of launch site (0.43412) indicated that for every 1-letter increment of the launch-site distance from the space in front of the test words, landing positions shifted on average by slightly less than half a letter towards the words' beginning. The launch-site effect mildly increased as the test words became longer, as suggested by the significant interaction between launch site and word length (estimate: 0.04732), thus in contrast with McConkie et al.'s [18] original report of an invariant (0.49) linear relationship between word-center-based launch site and landing site. However, this was not due to launch site being here expressed relative to the space in front of the words. Indeed, LME analyses with launch-site distance expressed relative to the center of words, and for words of either 3-11 letters or 4-8 letters as in McConkie et al.'s study, also yielded significant interactions between launch site and word length (estimates: 0.05441 and 0.05925 respectively; see S1 Table). Note though that the effect of word length was no longer significant, at least in analyses restricted to 4- to 8-letter words as in their study (estimate: -0.03716, t = -1.40487); for 3- to 11-letter words, this effect was marginally significant (estimate: -0.04157; t = -1.91692).

Table 6. Fixed effects of LME model for the initial landing positions in the test words.

	Estimate	Std. Error	t value
(Intercept)	-0.55607	0.11520	-4.82683
FREQ	0.02389	0.01828	1.30705
PRED	0.02116	0.01186	1.78409
LENGTH	-0.20229	0.02226	-9.08598
LAUNCH	0.43412	0.02495	17.39834
FREQ:PRED	-0.00101	0.00728	-0.13910
FREQ:LENGTH	0.02867	0.00931	3.07860
PRED:LENGTH	0.01512	0.00685	2.20722
FREQ:LAUNCH	0.00839	0.00577	1.45530
PRED:LAUNCH	0.00591	0.00509	1.16075
LENGTH:LAUNCH	0.04732	0.00518	9.13987
FREQ:PRED:LENGTH	0.00493	0.00390	1.26396
FREQ:PRED:LAUNCH	0.00015	0.00331	0.04639
PRED:LENGTH:LAUNCH	-0.00207	0.00302	-0.68398
FREQ:LENGTH:LAUNCH	0.00526	0.00299	1.76243

Initial eye landing positions were expressed in letters relative to the center of the test words. Word length (“LENGTH”; 3-11 letters), word frequency (“FREQ”; between -1.97 and 7.16 log units), word predictability (“PRED”; between -2.60 and 2.60 logit units), and saccadic launch-site distance (“LAUNCH”; between -8.00 and -0.002 letters from the space in front of the test words), as well as all possible two- and three-way interactions, were entered as predictors. The random structure included a random intercept by participant and by sentence pair, as well as by-participant random effects of word length, word frequency, word predictability and saccadic launch-site distance. The intercept estimate gives the initial landing position when all variables were at their reference, mean, value (Word Length: 6.20 letters; Launch Site: -4.39 letters; Word Frequency: 2.91 log units; Word Predictability: -0.97 logit units). Colon stands for interaction.

More critical for a test of word-based models, was whether linguistic factors would significantly influence within-word landing positions. As shown in Table 6, the frequency of the test words had no significant effect (estimate: 0.02389, p = 1.30705), while word predictability only had a marginally significant effect (estimate: 0.01925, p = 1.76). Still, there were significant interactions between word frequency and word length (estimate: 0.02867), and word predictability and word length (estimate: 0.01512). As illustrated in Fig 8A-B, where the model’s predictions were represented, using the two most extreme word-frequency and word-predictability values across all test words, saccades landed further into more frequent, and to a lesser extent more predictable, test words, but progressively more as word length increased, and actually only when the words were longer than 5 letters. The marginally significant interaction between word frequency, word length and saccadic launch-site distance (estimate: 0.00526, t = 1.76243), suggested in addition that the tendency for saccades to land further into more frequent words, tended to become greater with decreasing launch-site distance, and even more so as word length increased (see Fig 8C). Yet, however consistent the effects of word frequency and word predictability were, they remained much smaller than the effects of launch-site distance and word length, and they were actually smaller than represented in Fig 8A-C. This is further illustrated in Fig 8D, where the models' predictions were re-plotted, but for the two most extreme word-frequency values for each word length separately, thus taking into account the much smaller range of word frequencies with increasing word length.

Fig8. Estimated initial landing positions in the test words.

Initial landing positions in the test words, as predicted by LME modeling (see also Table 6), represented as a function of word length (in letters; A-B), and for 4-,6-,8-, and 10-letter test words as a function of saccadic launch-site distance (in letters relative to the space in front of the test words; C-D), separately for the two most extreme word-frequency values across all test words (-1.97 vs. 7.16 log units; A,C), the two most extreme word-predictability values across all test words (-2.60 vs. 2.60 logit units; B), or the two most extreme word-frequency values across all test words of a given length (4-letter words: -1.97 vs. 6.76 log units; 6-letter words: -1.61 vs 5.79 log units; 8-letter words: -0.62 vs. 4.29 log units; 10-letter words: -0.30 vs. 3.62 log units; D).

In sum, both the frequency and the predictability of the test words influenced within-word landing positions, but only when the test words were long enough for the frequency-related shift in landing-site distributions to take place within the word boundaries (see Fig 1 and 7A-B), and also essentially when saccades' launch-site distance was small enough so that the words could benefit from peripheral preview [see also 55]. This clearly demonstrates, in contradiction with existing word-based models, that language-related variables nearly equally influence the likelihood of word skipping and within-word initial landing positions, and that one or the other occurs depending on the word's length. Thus, in line with the non-word based view, ongoing linguistic processing would overall modulate the length of forward saccades, regardless of word boundaries. Where the eye moves next would still be primarily a function of the words' length and the saccades' launch-site distance to the beginning of the words [see also 9, 18, 26, 27, 33, 70]. Indeed, these two variables more greatly influenced both word-skipping probability and within-word landing positions, compared to the frequency or the predictability of words.

Within-word initial landing positions across all words in the sentences

In the above, test-word, analyses, we reported tiny effects of linguistic variables on initial landing positions in longer and less eccentric words. To ensure that this pattern was not due to the specific (linguistic) properties of the test words, and that it could be observed at a larger scale and with a greater number of observations, we conducted again the same analyses, but using this time all words in the sentences that responded to the above-selection criteria (see Materials and Methods).

In Fig 9, the distributions of initial landing positions in short, and long words (3-4 letters and 7-8 letters respectively), were plotted separately for different saccades' launch-site distances to the space in front of the words, and for two categories of word frequencies (low vs. high; see Figure Legend). These again showed, in line with the well-established launch-site effect, that landing-site distributions shifted towards the words' end as saccades were launched from closer to the words' beginning [18]. Most importantly, in near and intermediate launch-site cases (> -7 letters), that favored peripheral preview, there was an overall tendency for the distributions to peak slightly further into high- compared to low-frequency words of 7 and 8 letters, thus when the distributions peaked near the center of words. In short (3- and 4-letter) words, to the contrary, there was no clear word-frequency related shift in landing-position distributions, at least within the word boundaries. Thus, the pattern reported above for the test words replicated here.

Fig9. Within-word landing-position distributions.

Across-participants probability density functions (bandwidth: 1 letter or 0.25°; Gaussian Kernel) of initial landing positions in short and long words (3-4 letters and 7-8 letters in left and right panels respectively), and for different saccadic launch-site distances binned in one-letter intervals (from upper to lower panels: -1,-3,-5, and -7 letters respectively relative to the space in front of the words), separately for the two most extreme categories of word frequencies grouped into four bins (see Materials and Methods). Light-grey rectangle areas represent the horizontal extent of the words.

The fixed effects of corresponding LME analyses are presented in Table 7. The emerging pattern was consistent with that observed for initial landing positions in the test words. Saccades initially landed at a position slightly to the left of the words' center when all variables were at their reference (mean) value, and words were about 6 letters long (intercept estimate: -0.61265). As words were shorter and less eccentric, saccades landed closer to the words' end, as suggested by the negative and positive slope estimates for the effects of word length and saccadic launch-site distance (-0.22617 and 0.35410 respectively) . The interaction between launch-site distance and word length was significant (estimate: 0.04389), indicating that the launch-site effect became slightly greater with increasing word length. This was again unrelated to launch-site distance being expressed relative to the space in front of the words; when within-word landing positions were re-analyzed as a function of word length and word-center-based launch-site distance, the interaction remained significant, though not the effect of word length (see S2 Table).

Table 7. Fixed effects of LME model for within-word initial landing positions

	Estimate	Std. Error	t value
(Intercept)	-0.61265	0.07980	-7.67701
FREQ	0.01566	0.00943	1.65989
LENGTH	-0.22617	0.01589	-14.23775
LAUNCH	0.35410	0.01679	21.08889
FREQ:LENGTH	0.01654	0.00210	7.86553
FREQ:LAUNCH	-0.00198	0.00209	-0.94533
LENGTH:LAUNCH	0.04389	0.00259	16.96980
FREQ:LENGTH:LAUNCH	0.00423	0.00076	5.55775

This analysis was conducted across all words in the sentences that responded to our selection criteria (see Materials and Methods). Initial landing positions were expressed in letters relative to the center of words. Word length (“LENGTH”; 3-11 letters), word frequency (“FREQ”; between -2.66 and 9.59 log units), and saccadic launch-site distance (“LAUNCH”; between -9.99 and -0.001 letters from the space in front of the words), as well as all possible interactions, were entered as predictors. The random structure included a random intercept by participant and by sentence, as well as by-participant random effects of word frequency, word length and launch-site distance. The intercept estimate gives the initial landing position when all variables were at their reference, mean, value (Word Length: 5.94 letters; Launch Site: -4.86 letters; Word Frequency: 4.11 log units). Colon stands for interaction.

Most importantly, there was again no significant effect of word frequency on within-word initial landing positions (estimate: 0.01566; $p = 1.66$), but both the interaction between word frequency and word length and the interaction between word frequency, word length and launch-site distance were significant (estimate: 0.01654 and 0.00423 respectively). The positive slope estimates indicated a tendency for saccades to land slightly closer to the words’ end as their frequency increased, with this tendency becoming greater in longer words, and even more so as the saccades were launched from closer to the words' beginning. This is illustrated in Fig 10A-B, where the model’s predictions for the effects of word length and launch-site distance were represented for the two most extreme word-frequency values across all selected words. From this figure, it is again quite clear that the effect of word frequency remained relatively small in comparison with the effects of word length and launch site. This was only a third of the effect of launch-site distance in the most optimal conditions (longest word and smallest launch-site distance), and actually even less since the range of word frequencies for a given word length was less than the range of word frequencies across all words (see Fig 10C). Still, the fact that there was an effect of word frequency at least in long words does suggest that within-word landing positions, just as word-skipping likelihood, are slightly modulated by language-related variables.

Fig10. Estimated within-word landing positions.

Within-word initial landing positions for all words in the sentences, as predicted by LME modeling (see also Table 7), as a function of word length (in letters; A), and for 4-, 6-, 8-, and 10-letter words as a function of launch-site distance (in letters relative to the space in front of the words; B-C), separately for the two most extreme word-frequency values across all selected words regardless of their length (-2.66 and 9.59 log units respectively; B), and across all selected words of a given length (4-letter words: -1.97 vs. 9.02 log units; 6-letter words: -1.97 vs. 6.30 log units; 8-letter words: -1.97 vs. 6.13 log units; 10-letter words: -2.66 vs. 3.88 log units; C).

In sum, despite word length and launch site were strong predictors of initial landing positions in words, word frequency did also slightly, though significantly, contribute. Importantly, its impact was greater when landing positions were on average away from the word boundaries, as in the case of long words, and when the saccades were launched from close enough to the words' beginning so that the words could benefit from peripheral preview.

This is clearly in contradiction with predictions from word-based models, but in line with the assumption that saccades are overall slightly modulated by linguistic processing, regardless of word boundaries.

Overall landing positions (regardless of word boundaries)

In the above analyses, we found that word frequency, and to some extent word predictability, not only influenced the likelihood of word skipping, but also within-word landing positions, at least for some word lengths and/or saccadic launch-site distances. Critically, while word frequency had a greater impact on the likelihood of skipping shorter words, it influenced almost exclusively saccades' initial landing positions in long words. These findings, in contradiction with the predictions from word-based models, provided a first set of evidence for the hypothesis that ongoing peripheral word-identification processes overall modulate where the eye moves, regardless of word boundaries.

The non-word-based view makes yet another, more direct, prediction. It predicts that saccades should land further on the line of text when the word immediately to the right of fixation (N+1) is easier to process, and even more so in optimal peripheral preview conditions, that is when the word is shorter and less eccentric. To test this prediction, we thus re-analyzed the data, but measuring this time the landing positions of all saccades launched from a given word (N), regardless of the word they landed on, as a function of the properties of Word N+1 and saccades' launch site distance to the space in front of Word N+1. These overall landing-position analyses, unlike the above analyses, did not imply word-based truncation of landing-site distributions [see also 70-72]. Saccades between 0 and n words in length were assumed to belong, at least by default, to the same population, thus allowing a more objective/neutral test of word-based vs. non-word based hypotheses, while avoiding limitations due to floor/ceiling effects as in the above word-skipping rate and within-word landing-position analyses.

These overall saccadic landing-position analyses were conducted only across all words in the sentences. Indeed, given the wider range of possible landing positions, in comparison with within-word landing positions, the n was too low for these analyses to be conducted over the test words only. The same selections as for within-word landing-position analyses were applied, except that the fixation of interest was part of the first eye pass on a word, and hence not necessarily the first fixation on a word: this corresponded either to a refixation of Word N or the first fixation on one of the following words (Word N+1, N+2...). The critical word, N+1, was between 3 and 11 letters, not the last word on the line, not preceded or followed by punctuation, and not a compound word, while Word N was never the first word on the line. In addition, the fixation of interest was within a window of -10 to 20 letters around the center of Word N+1.

Assuming non-word-based eye-movement guidance, we expected that overall landing-site distributions would shift further towards the end of the line for high- compared to low-frequency N+1 words, though more largely as the words were shorter and less eccentric. In contrast, word-based models, predicted at least bimodal distributions, centered respectively on Words N+1 and N+2, with a smaller peak associated with high- compared to low-frequency N+1 words, but no word-frequency related shift in landing positions. As further detailed below, the data were inconsistent with these latter predictions, arguing instead for non-word-based eye-movement guidance.

In Fig 11, overall landing-site distributions across all words in the sentences were plotted for two categories of word frequencies (low vs. high; see Figure Legend), separately for short (3- and 4-letter) and long (7- and 8-letter) words and for different saccadic launch-site distances (in 2-letter bins). The distributions were for the great majority unimodal. There was only a tendency for the right tail of landing-site distributions to be elongated in the case of longer and less eccentric words (upper right panels), as well as a tendency for somewhat bimodal distributions at the largest launch sites (lower panels), although it is hard to tell whether the latter was due to a lack of data or within-word refixations forming a separate population. In any case, there was clearly no evidence for the distributions to exhibit two distinct modes, with one centered on Word N+1, and the other centered on Word N+2. Actually, most saccades landed beyond the end of very short (3- and 4-letter) N+1 words, and within the boundaries of long (7- and 8-letter) N+1 words, with the exact landing position relative to the beginning of N+1 words being primarily a function of the saccades' launch-site distance to the space in front of the words as well as the words' length. As saccadic launch-site distance increased, the distributions shifted leftward, peaking closer to the end/center of short words, and the very-beginning of long words (or in front of it). Moreover, as word length increased, the distributions peaked slightly closer to the words' beginning. Most importantly, there was a slight, though quite consistent, rightward shift in landing-site distributions with increasing word frequency; this indicated that saccades tended to land slightly further as N+1 words were more frequent, though to greater extents when the words were shorter (and in particular 4 letters long) and not too far out in the periphery (< 7 letters). As a result, word frequency nearly exclusively influenced the likelihood of word skipping in the case of short words, while mainly affecting within-word landing positions in the case of long words, in line with the above analyses.

Fig11. Overall landing-position distributions.

Across-participants probability density functions (bandwidth: 1 letter or 0.25°; Gaussian Kernel) of all saccades' landing positions regardless of word boundaries (or overall landing positions), expressed in letters relative to the beginning of Word N+1 (i.e., the word immediately to the right of the word (N) from which the saccade was launched), with positive values corresponding to landing positions on this word or beyond it, and negative values corresponding to landing positions in front of the word, and hence refixations of Word N. Distributions were plotted, using all words in the sentences that responded to our selection criteria (see Text), separately for short and long N+1 words (3-4 and 7-8 letters in left and right panels respectively), different saccadic launch-site distances (in letters relative to the space in front of Word N+1), binned in two-letter intervals (from upper to lower panels: [0,-2[, [-2,-4[, [-4,-6[, [-6,-8[, referred to as -1,-3,-5 and -7 respectively), and for high vs. low-frequency N+1 words (i.e., the words that fell respectively within the two most extreme categories of word frequencies when grouped into three bins; see Materials and Methods). Light-grey rectangle areas represent the horizontal extent of the words.

LME models were fitted to overall saccadic landing positions, as measured from the beginning of N+1 words, using the same cut-off selections for word length and launch-site distance as in within-word landing position analyses. As shown in Table 8, where the model's fixed effects were reported, saccades landed 1.3 letters away from the beginning of N+1 words, when all variables were at their reference, mean, value, and words were about 5 letters long. The positive slope estimate for the effect of launch-site distance (0.89519), indicated that landing positions shifted by only a bit less than one letter for every one-letter increment of the launch-site distance, thus suggesting that the launch-site effect more than doubled its size when all saccades' landing positions, instead of only within-word landing positions, were considered for analysis (see Table 7 for comparison). Note that this was not a result of saccades' landing positions being measured relative to the beginning of N+1 words. When data were re-analyzed using word-center-based launch sites and landing sites, a similar slope was obtained (estimate: 0.90056; S3 Table).This first result confirms that the launch-site effect extends well beyond the word boundaries [26, 27, 44], while showing that its slope varies with how data are analyzed. In the discussion below, we will see that this is also inconsistent with predictions from word-based models.

Table 8. Fixed effects of LME model for overall landing positions.

	Estimate	Std. Error	t value
(Intercept)	1.31088	0.21148	6.19851
FREQ	0.09892	0.01563	6.32832
LENGTH	-0.47329	0.02157	-21.94641
LAUNCH	0.89519	0.02466	36.29666
FREQ:LENGTH	-0.02635	0.00442	-5.96636
FREQ:LAUNCH	-0.00243	0.00452	-0.53832
LENGTH:LAUNCH	0.00567	0.00734	0.77338
FREQ:LENGTH:LAUNCH	-0.00292	0.00180	-1.62310

Were considered for analysis, the landing positions of all saccades regardless of word boundaries; these were expressed in letters relative to the beginning of Word N+1, that is the word immediately to the right of the word (N) from which the saccade was launched. Word N+1 was not necessarily a test word (see Text). Word length ("LENGTH"; 3-11 letters), word frequency ("FREQ"; between -2.66 and 9.59 log units), and saccadic launch-site distance ("LAUNCH"; between -9.99 and -0.001 letters from the space in front of Word N+1), as well as all possible interactions, were entered as predictors. The random structure included a random intercept by participant and by sentence, as well as by-participant random effects of word frequency, word length and saccadic launch-site distance. The intercept estimate gives saccades' landing position when all variables were at their reference, mean, value (Word Length: 5.43 letters; Launch Site: -3.39 letters; Word Frequency: 5.43 log units). Colon stands for interaction.

The model's fixed effects additionally revealed a significant effect of word length, suggesting that saccades landed closer to the beginning of longer N+1 words (estimate: -

0.47329). More critically, there was a significant effect of word frequency (estimate: 0.09892), as well as a significant interaction between word frequency and word length (estimate: -0.02635). This indicated that saccades landed further away with increasing word frequency, and even more so as words were shorter and hence more greatly benefited from peripheral preview. As shown in Fig 12, where the model's predictions were represented for the two most extreme word-frequency values across all selected words, there was a clear word-frequency effect for short, 3- and 4-letter, words. Given that these words were most often skipped, this indicates that even word-skipping saccades landed at different locations on the line depending on the words' frequency. The additional fact that the word-frequency effect extended to words as long as 8 letters, that were most often fixated, confirmed the above-reported effect for within-word landing positions.

Fig12. Estimated overall landing positions

Overall saccades' landing positions for all words in the sentences, as predicted by LME modeling (see also Table 8), as a function of word length (in letters), separately for the two most extreme word-frequency values across all selected words (-2.66 and 9.59 log units respectively).

Thus, contrary to the predictions made by word-based models, but in line with the non-word-based view, linguistic variables did influence where the eye moved on the line of text, regardless of word boundaries. Their effects were smaller in longer words, that less largely benefited from peripheral preview, and much smaller compared to the effects of saccadic launch-site distance and word length, therefore suggesting that these modulated only occasionally the length of default forward saccades, as determined based on low-level visuo-motor processes.

Discussion

To test the general hypothesis that eye movements during reading are purposely guided from one word to another word based on the needs of word-identification processing, we re-examined the long-studied influence of language-related variables on forward eye-movement behavior, but using LME modeling applied to a large and well-controlled sentence-reading data set. We found that the words' frequency of occurrence in the language, and their predictability from the sentence context (in the case of test words), only mildly influenced where the eye moved next, in comparison with the words' length and the saccades' launch-site distance to the beginning of words. Nevertheless, frequency and predictability affected not only the likelihood of word skipping, but also within-word landing positions, all depending on the words' length and eccentricity. Words that were shorter (3-5 letters long), and also closer to the saccade's launch site, were more often skipped, and even more so as their frequency, and/or their predictability increased. However, as word length increased, the likelihood of word skipping became both smaller and less strongly affected by word frequency/predictability, while within-word landing positions, closer to the words' center, started showing variations with frequency and predictability. As suggested in further analyses, these effects came from an overall slight shift of saccades' landing positions towards the end of the line of text, with increasing easiness of Word N+1. In the next sections, we explain how these novel findings contradict the predominant word-based account of eye-movement control during reading. We then argue, in line with Vitu's [5, 6] non-word-based hypothesis, that saccades drive the eye forward along the lines of text regardless of word boundaries, primarily as a result of low-level visuo-motor mechanisms, and only exceptionally based on ongoing language-related processes.

Evidence against word-based eye-movement guidance

The general hypothesis, in models of eye-movement control during reading, that saccades are invariably programmed towards the center of online-defined target words was established based on two main arguments. The first relates to the many empirical findings showing that the words that are skipped tend to be easier to process in peripheral vision: they are highly frequent [e.g., 29, 30], highly predictable [e.g., 32], shorter [9], nearer to the saccades' launch site [26, 27], and/or visible rather than being masked in peripheral vision [e.g., 28]. The second argument relates to the well-established fact that within-word landing positions systematically vary with saccades' launch-site distance to the center of words [18], but fail to show clear and consistent variations with the words' orthographic and linguistic properties [for reviews see 6, 34].

Our results first confirmed that the likelihood of word skipping varies with both word length and saccadic launch-site distance, as well as with word frequency and to a lesser extent word predictability. However, frequency and predictability effects, which occurred mainly in shorter and less eccentric words, remained much smaller in comparison with the effects of word length and launch-site distance [see also 26, 33]. These first findings may be hard to explain based on the hypothesis made in E-Z Reader and SWIFT, that eye-movement guidance nearly exclusively relies on ongoing lexical processing [1, 2]. They are still consistent with the assumption in other word-based models, that eye-movement guidance firstly relies on selection of a visual blob in the periphery, as determined based on ongoing non-lexical visual processing (i.e., visual acuity function [4, 73]), or educated guesses related to the information content of peripheral words [3]. However, whether blob-based guidance would sensibly account for the previously reported observation, during the reading of meaningless z-texts, that the likelihood of skipping z-letter strings decreases progressively with increasing string length and launch-site distance [see also 37, 38], remains debatable.

Since z-letter strings have no linguistic content and are 100% predictable, they should always be skipped, regardless of their length, unless word-skipping behavior reflects hard-wired pre-determined visuo-motor scanning routines that cannot be turned-off in the absence of linguistic content and/or in low uncertainty conditions [see 11, 12].

Our landing-position findings however provided further and unambiguous arguments against a word-(object-)based account of eye-movement guidance during reading. The first relates to our observation that within-word landing positions were part of a larger distribution of saccades' landing positions, that largely extended outside the word boundaries. The fact that these overall landing-site distributions appeared to be most often unimodal is already in contradiction with the prediction made by word-based guidance, that there should be as many modes as possible target words (minimally the next word, N+1, and the word following it, N+2). The additional finding that these distributions shifted by about 0.9 letter towards the beginning of Word N+1 (or even in front of it) with every one-letter increment of the saccades' launch-site distance to Word N+1 simply cannot be accounted for by the general hypothesis that saccades' landing positions result from a compromise between a word-center targeting strategy and SRE. This hypothesis was proposed precisely because it was thought that there is a relatively invariant linear relationship between launch site and landing site, with a typical slope of 0.5, that is just halfway between a slope of 0 that would indicate that the eye always lands at the center of words, and a slope of 1 that would reflect a tendency to make constant eye steps forward [see 18]. Using the same rationale, the here-observed slope of 0.9 would mean that saccades in our study were mostly driven by SRE, and hence mostly prone to move the eye a constant distance forward. However, this was unlikely the case because saccades' landing positions were also strongly influenced by the length of peripheral words. Note in addition, that several previous studies actually showed that the slope of the linear relationship between launch site and within-word landing site is not invariant, but rather depends on the peripheral visual configuration [72, 74, 75]. Accordingly, but in contradiction with McConkie et al.'s [18] original findings, we found that the effect of launch-site distance on within-word landing positions became stronger with increasing word length.

Another strong argument against word-based guidance came from our finding that within-word landing positions were not exclusively influenced by saccadic launch-site distance and word length, but also depended on the words' linguistic properties. Just like word-skipping rate slightly increased with increasing word frequency and to some extent also word predictability, within-word landing positions shifted closer to the end of words as they were more frequent or more predictable. The fact that these language-based effects on within-word landing positions intervened mainly in long words, while the same effects on word-skipping likelihood occurred mainly in short words, is not surprising when considering that analyses of within-word landing positions rely on truncated landing-position distributions. Since saccades' overall landing-position distributions peak towards the center of long words, but near the very end of short words or even beyond it, they can yield effects of linguistic factors on within-word landing positions mostly in long words (see Fig 1). The fact yet that less information can be gathered from long words, in comparison with short words, in peripheral vision, in combination with the slowness of language-related processes [48, 49], explains why these effects remained tiny. It also accounts for the fact that many previous studies failed to observe these effects [52, 54]. Effects of word predictability on within-word landing positions were still found in a couple of studies and in conditions similar to ours. In particular, Lavigne et al. [55] reported semantic predictability effects in words that were 6-8 letters long, but only when the words were highly frequent and when they could benefit from peripheral preview (launch-site distances equal to or less than 7 letters from the words' beginning). The fact that Rayner et al. [36] failed to replicate this finding and only observed a tiny, though non-significant, effect of word predictability at close-launch sites, was likely due to their words being shorter (5-6 letters), on top of word predictability being not controlled with a cloze task: as the distributions peaked very near to the end of words (at least in their Experiment 2), the effect mainly took place beyond the word boundaries, being significant only for the likelihood of word skipping.

Our additional finding that the effect of word frequency on landing positions generalized to, and was actually greater in, short words when the full distributions of saccades' landing positions on the line of text, instead of truncated within-word landing position distributions, were considered, further strengthens our interpretation of previous word-based results. It also suggests that word-based analyses of saccadic behavior can be misleading, while providing another strong case against word-based guidance. Assuming that ongoing peripheral word-identification processes only have all-or-none influences on selection of a saccade target word simply cannot lead to the prediction that skipping as well as non-skipping saccades would land further away from the beginning of Word N+1 as this becomes easier to process.

Thus, in contradiction with the predominant word-based account of eye-movement guidance, saccades do not seem to be invariably programmed towards the center of peripherally defined target words, and where they actually land very unlikely reflects a compromise between this word-center targeting strategy and SRE. Rather, where on the line of text (and with respect to word boundaries) the eyes move next would primarily be a function of the visual peripheral configuration on a given eye fixation, and hence would depend on the saccade's launch-site distance to the beginning of the next word as well as the word's length. Language-related processes would intervene by overall modulating saccades' landing positions, thus regardless of word boundaries, rather than exclusively determining the likelihood of word skipping. However, this would happen essentially when all conditions are met for an optimal peripheral preview of the next word(s), and even more so when the linguistic properties of the words (frequency or predictability) further reduce the uncertainty of the upcoming word(s).

An alternative, non-word-based, account of eye-movement control.

Yang and McConkie [7, 8] were the first to discuss the hypothesis that eye movements during reading may not be guided in a word-based manner. Their main argument was that inter-word spacing, and even more so word information content, are not available until late during a fixation (i.e., not before about 175-200 ms and 225-250 ms from fixation onset respectively), and therefore that many saccades must be generated autonomously, before this information is extracted. On that basis, they proposed the Competition/Interaction (C/I) model. This model relies on the assumption that saccadic eye movements are by default purely guided by strategy-based activation, or a bias to move the eye a constant distance forward [see also 76, 77]. Strategy-based activation is similar to SRE, although it is not in this framework a source of error for otherwise goal-directed movements, but rather the default eye driving force. Visually-based guidance would kick in later, when visual input is available, that is no earlier than about 175 ms from fixation onset. Being a function of letter-based activation, as weighted by letter eccentricity, letter-distance to the center of words and word length, this would lead the eye to move in a somewhat word-based manner, and hence to preferentially land towards the center of words, and nearer to the words' beginning as word length and launch-site distance increase [17]. Ongoing language processing would also intervene, but much later: when a processing difficulty would be encountered, the planned saccade would be inhibited, delaying saccade onset and reducing mainly the propensity to move the eye forward.

Despite the fact that the C/I model is conceptually different from word-based models, it makes quite similar predictions, at least for the landing positions of forward saccades. It may thus fail, as word-based models, to account for several of our findings. First, given the range of fixation durations during reading, and the fact that 90% of them are longer than 150 ms, this model paradoxically predicts a major role of visual input, and hence word-object-based guidance, at the expense of strategy-based activation [17, see also 4, 73]. This first implies that landing-position distributions of forward saccades should be multimodal, with each mode aligned with a possible target word (see Figure 3 in Yang [17]), while as we have seen, these are in most instances unimodal, even when saccadic launch-site distance is taken into account. This implies in addition that the slope of the linear relationship between saccades' launch site and landing sites should be no greater than 0.5, and likely less (see above), thus in contradiction with the here-observed slope of 0.9. On the other hand, since ongoing language processing would intervene only through saccadic inhibition (that is inhibition of the region in the motor map coding for the planned saccade), it would modulate essentially the likelihood of regressive saccades, and to a lesser extent the likelihood of short-amplitude forward saccades (or within-word refixations), but not the landing positions of large-amplitude forward saccades. However, in contrast with this prediction, our findings revealed a slight though consistent influence of word frequency and word predictability on the landing positions of forward saccades. In addition, previous studies showed that regressive saccades are not preceded by longer fixation durations, as the model would predict [70, 78]. Thus, although we cannot reject all proposals made in the C/I model, this does not seem to propose a sensible and accurate account for where on the line of text the eyes land.

The alternative, center-of-gravity theory, that was originally proposed by Vitu [5, 6, 47, 79], may provide a more appropriate framework to account for the present findings. Indeed, unlike existing models, this incorporates neither selection of a saccade target word(-object), nor segmentation of the text into perceptual word units, to predict where the eyes land when moving forward. On any given eye fixation during reading, each letter on the line of text would be assigned a given level of activity, depending only on its visibility, and hence its eccentricity, regardless of the word it belongs to. Where the eye moves next would then directly derive from spatial-integration processes, the same processes that were shown to determine the metrical properties of saccades in simple saccade-targeting tasks. These processes take place in the Superior Colliculus, a midbrain structure that transforms visual input into the spatial code for a saccade [80]. As spatial coding in the SC is distributed over populations of neurons with large and overlapping receptive/movement fields, saccades move the eye to the location in space that corresponds to the center of the entire active population [81]. They therefore land by default near the center of gravity of the peripheral configuration, thus taking the eye away from their target when this is displayed simultaneously, with other, proximal, (distractor) stimuli [82, for a review see 5]; note that this is likely a weighted center of gravity, that is biased towards the fovea, given the magnification factor (or overrepresentation of regions closer to the fovea) in the SC [83, 84]. In a similar manner, saccades during reading would move the eye towards a weighted center of gravity of the global peripheral configuration formed by letters to the right of fixation, thus regardless of word boundaries [5, 79]. Therefore, in line with our findings, the resulting overall distribution of saccades' landing positions should be unimodal, and peak either beyond or within the next word on the line (N+1), depending on the word's length and the saccade launch-site distance to the beginning of the word. Saccades launched from close to the beginning of Word N+1 would tend to land beyond the end of the word when it is short, and near the end of the word when it is long, being pulled forward by material to the right of Word N+1. However, as saccades are launched from further away, their landing position would progressively shift towards the word's beginning, thus reproducing the well-known launch-site effect.

The center-of-gravity (or global) effect is a quasi-irrepressible oculomotor response, that vanishes only when saccade latency is greatly prolonged [85], and even more so as the visual array is visually more complex [86, 87]. Top-down, language-based, control is therefore not impossible, but given its slowness compared to earlier luminance-contrast signals (the earliest input to the SC[88]), it could only intervene punctually to modulate saccades' landing positions. This would be the case when fixation durations are prolonged, and/or when visual and linguistic variables combine to favor an early access to the word's representation. Thus, as we observed, the eyes would land further on the line of text as word frequency or word predictability increases, mainly when the word is both short and within the limits of the perceptual span for letter identity (< 6 letters [34]).

MASC, a model of Attention in the SC, did implement saccade-programming principles in the SC, taking into account many more SC constraints than originally envisaged by Vitu, to predict eye-movement behavior in a range of tasks [89]. As evidenced in a companion paper, its behavior while viewing sentences from the FSC, resembled very much reader's eye-movement patterns, even despite this being deprived of language-related knowledge and top-down control (see [90]). Yet, MASC showed some differences with readers, in line with the here-observed tiny linguistic influences, thus comforting our conclusion that eye-movement guidance during reading is primarily a result of low-level, non-word-based, visuo-motor processes, and only subject to one-off language-based modulations.

Conclusion

In contradiction with the long-standing assumption that saccadic eye-movements during reading are guided in a word-based manner, we have shown that the frequency and the predictability of words do not only affect the likelihood of word skipping, but also where in the words the eye lands, thus overall influencing saccades' landing positions regardless of word boundaries. These effects yet were small, and much smaller compared to the effects of word length and launch-site distance, which remained the best predictors of readers' eye movement patterns. Altogether these findings argue for the hypothesis that saccades during reading are primarily determined based on low-level visuo-motor mechanisms that require neither text segmentation nor selection of a saccade-target word(-object) in the periphery. Top-down, language-based, modulations of eye-movement behavior would intervene only in specific instances, in particular when the properties of the peripheral word(s) combine to allow a fast access to the words' representation.

Acknowledgments

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Supporting Information Caption

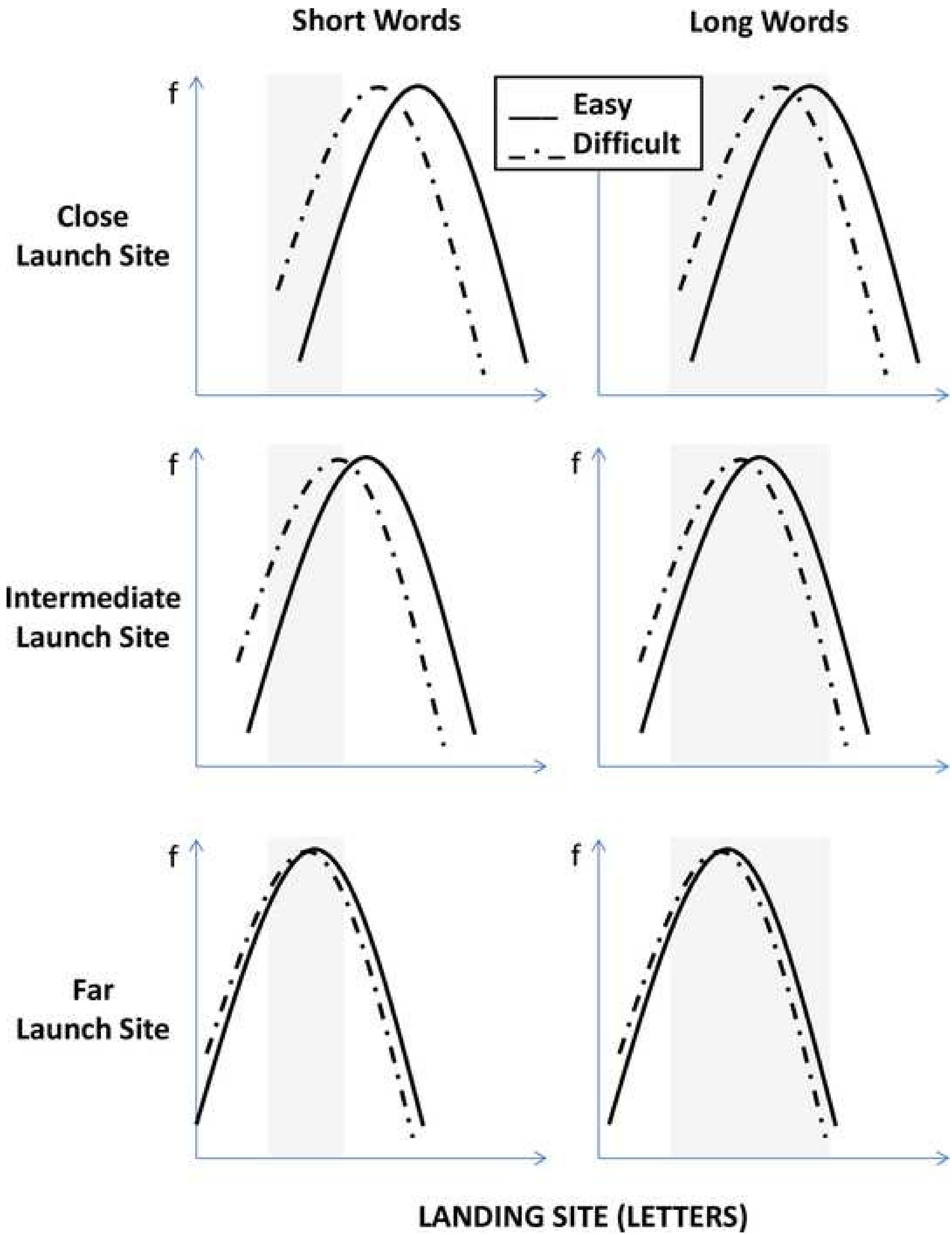
S1 Table. Fixed effects of LME model for the initial landing positions in the test words. Initial eye landing positions were expressed in letters relative to the center of the test words. Word length (“LENGTH”; 3-11 letters (a); 4-8 letters (b)) and saccadic launch-site distance (“LAUNCH”; between -14 and -4 letters from the center of the test words), as well as the interaction, were entered as predictors. The random structure included a random intercept by participant and by sentence pair, as well as by-participants random effects of word length and launch site. The intercept estimate gives the initial landing position when all variables were at their reference, mean, value (Word Length: 6.11 letters (a); 5.92 letters (b); Launch Site: -9.21 letters (a); -9.14 letters (b)). Colon stands for interaction.

S2 Table. Fixed effects of LME model for within-word initial landing positions. These analyses were conducted using all words in the sentences that responded to our selection criteria (see Materials and Methods). Initial eye landing positions were expressed in letters relative to the center of words. Word length (“LENGTH”; 3-11 letters (a); 4-8 letters (b)) and saccadic launch-site distance (“LAUNCH”; between -12 and -4 letters from the words’ center), as well as the interaction, were entered as predictors. The random structure included a random intercept by participant and by sentence, as well as by-participant random effects of word length and launch-site distance. The intercept estimate gives the initial landing position when all variables were at their reference, mean, value (Word Length: 5.79 letters (a); 5.88 letters (b); Launch Site: -8.28 letters (a); -8.21 letters (b)). Colon stands for interaction.

S3 Table. Fixed effects of LME model for overall landing positions.

Were considered for analysis all saccades' landing positions; these were expressed relative to the center of Word N+1. Word length ("LENGTH"; 3-11 letters) and saccadic launch-site distance ("LAUNCH"; between -12 and -2.50 letters from the center of Word N+1), as well as the interaction, were entered as predictors. The random structure included a random intercept by participant and by sentence, as well as by-participant random effects of word length and saccadic launch-site distance. The intercept estimate gives the landing position when all variables were at their reference, mean, value (Word Length: 5.04 letters; Launch Site: -6.77 letters). Colon stands for interaction.

Fig1



Short Words
Long Words
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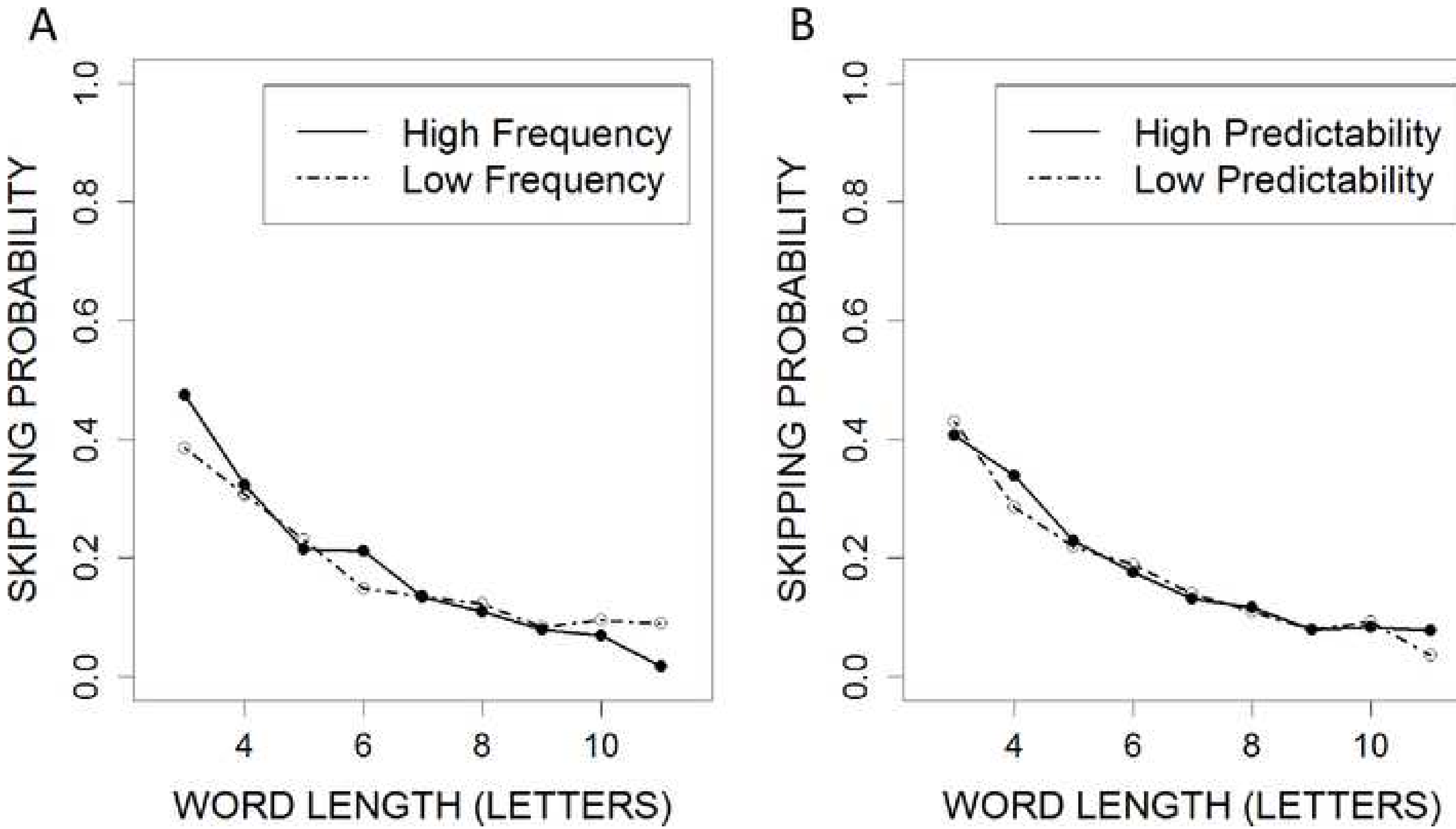
LANDING SITE (LETTERS)

Fig2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High Frequency
Low Frequency
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8
10
WORD LENGTH (LETTERS)
B
SKIPPING PROBABILITY
0.0
0.2
0.4
0.6
0.8
1.0
High Predictability
Low Predictability
4
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WORD LENGTH (LETTERS)

Fig3

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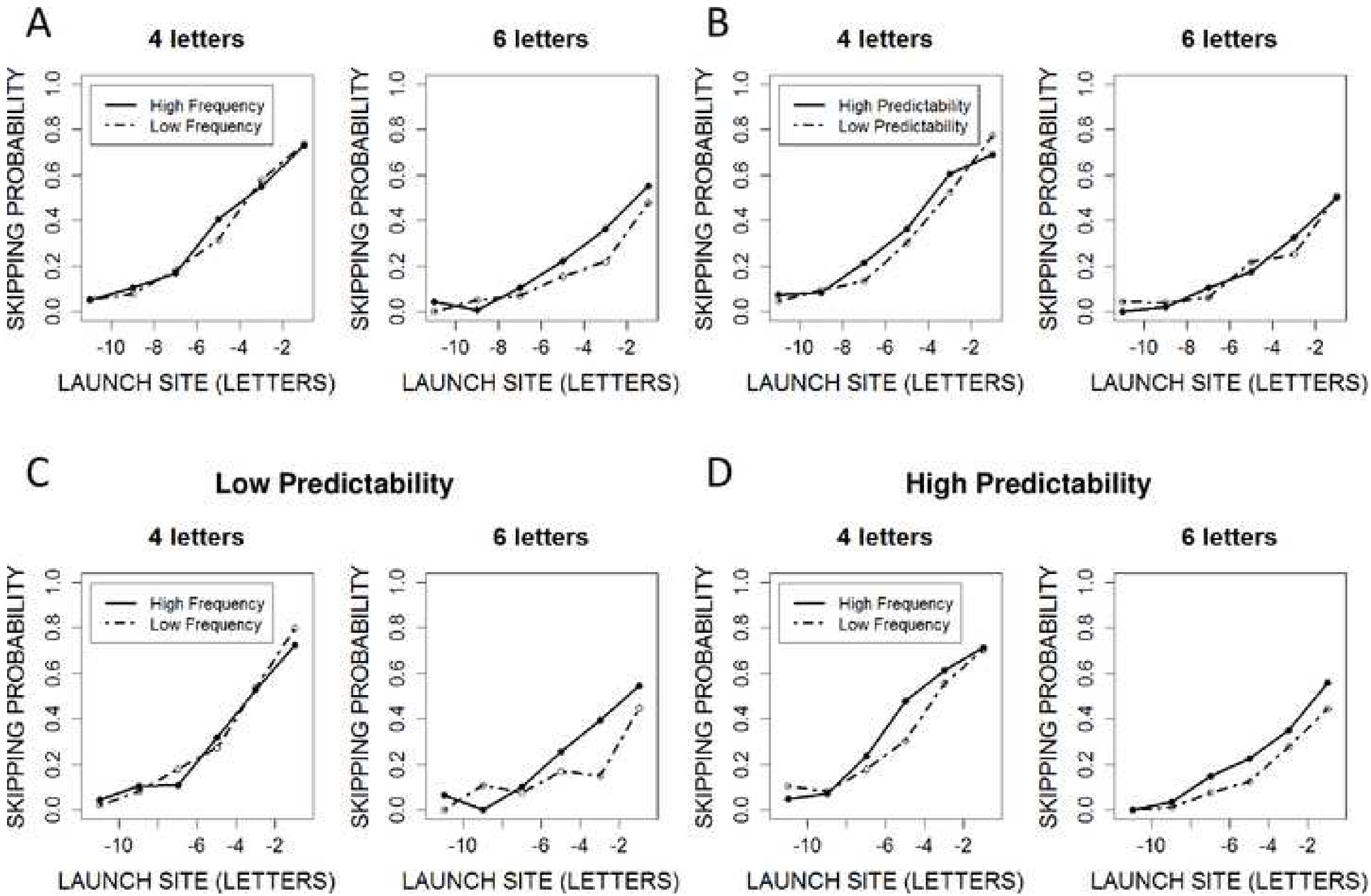

Fig4

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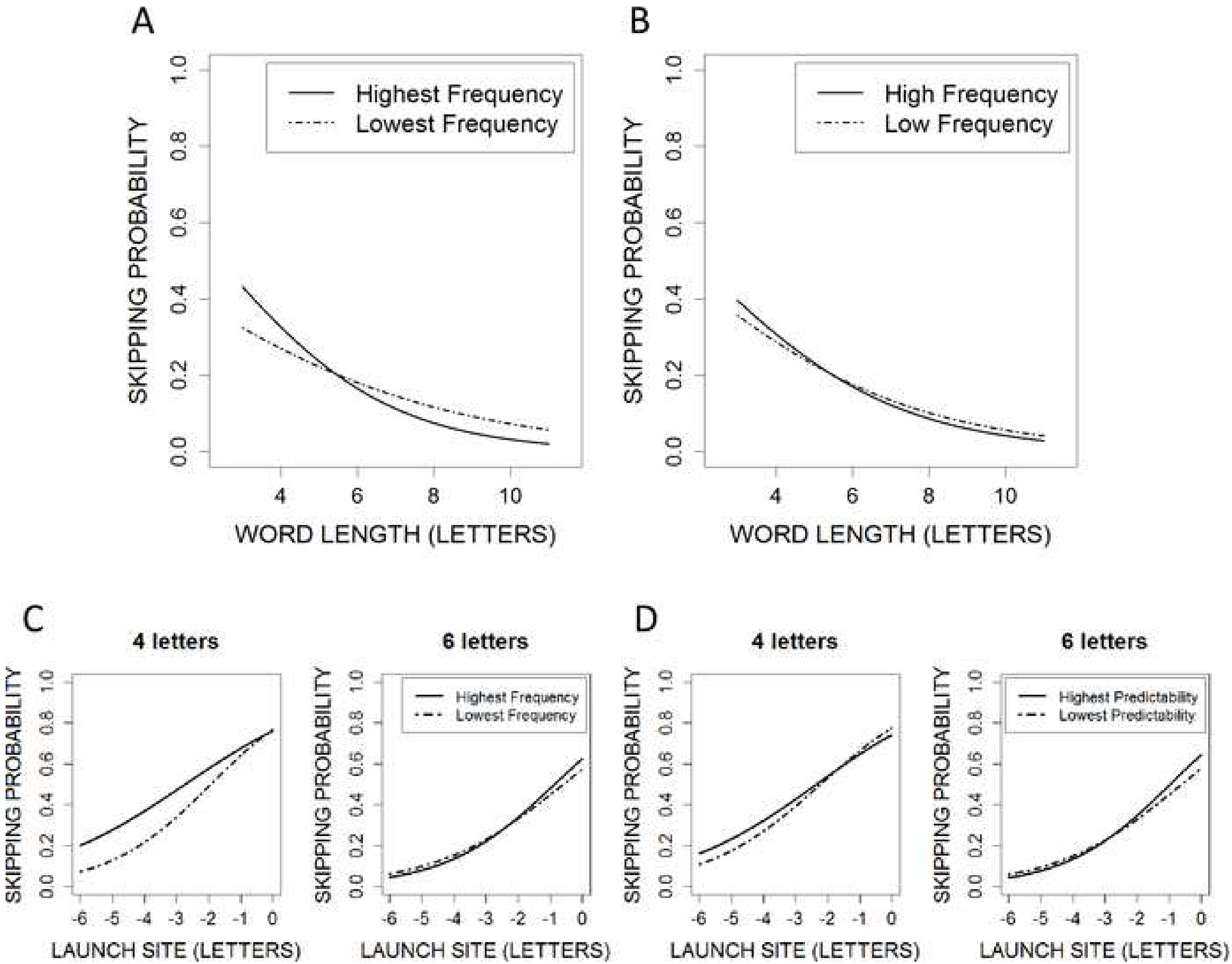

Fig5

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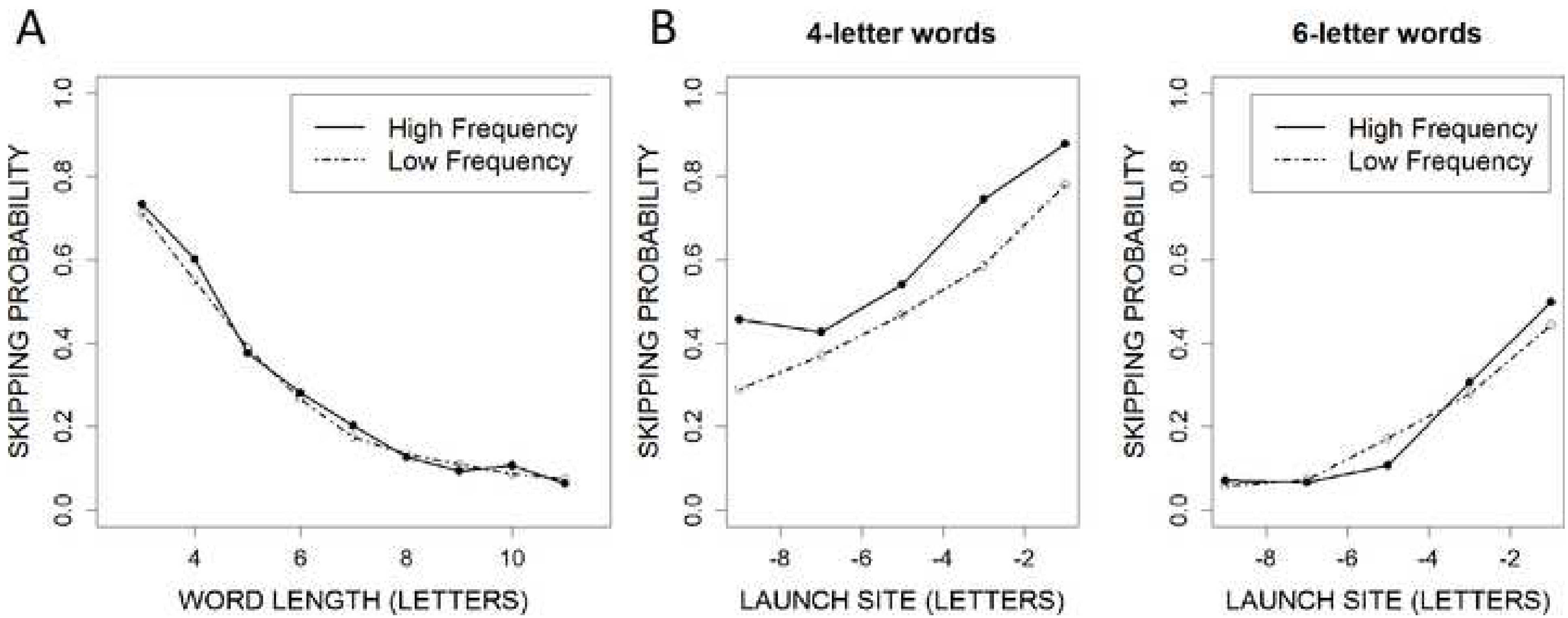

Fig6

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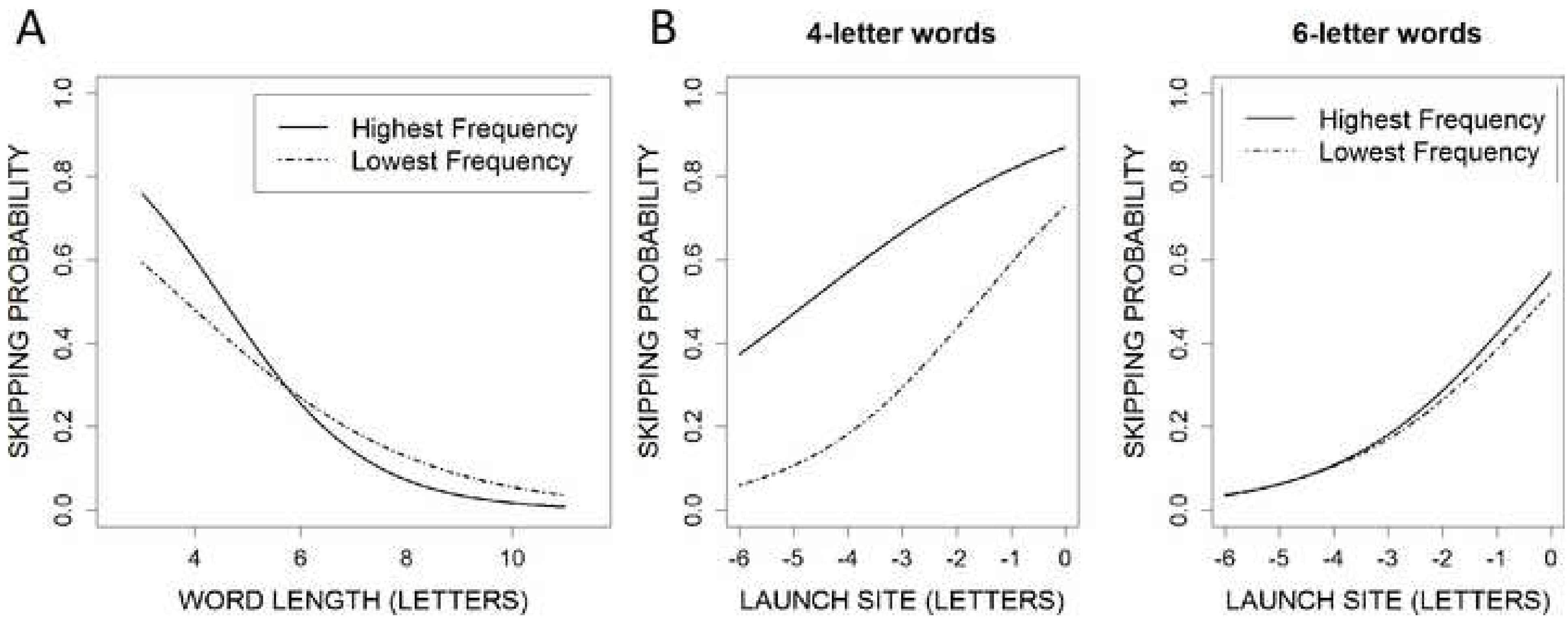

Fig7A

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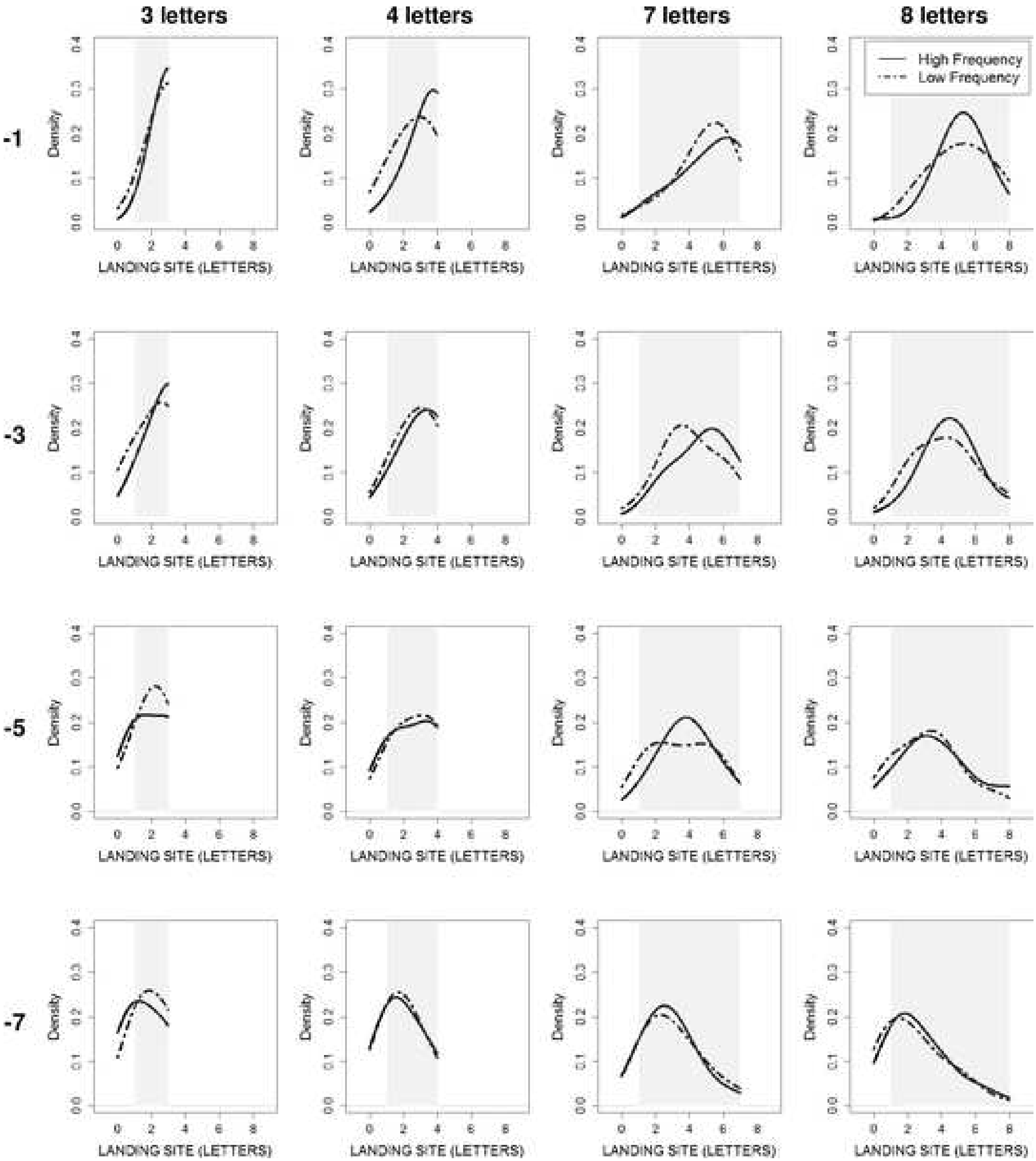

Fig7B

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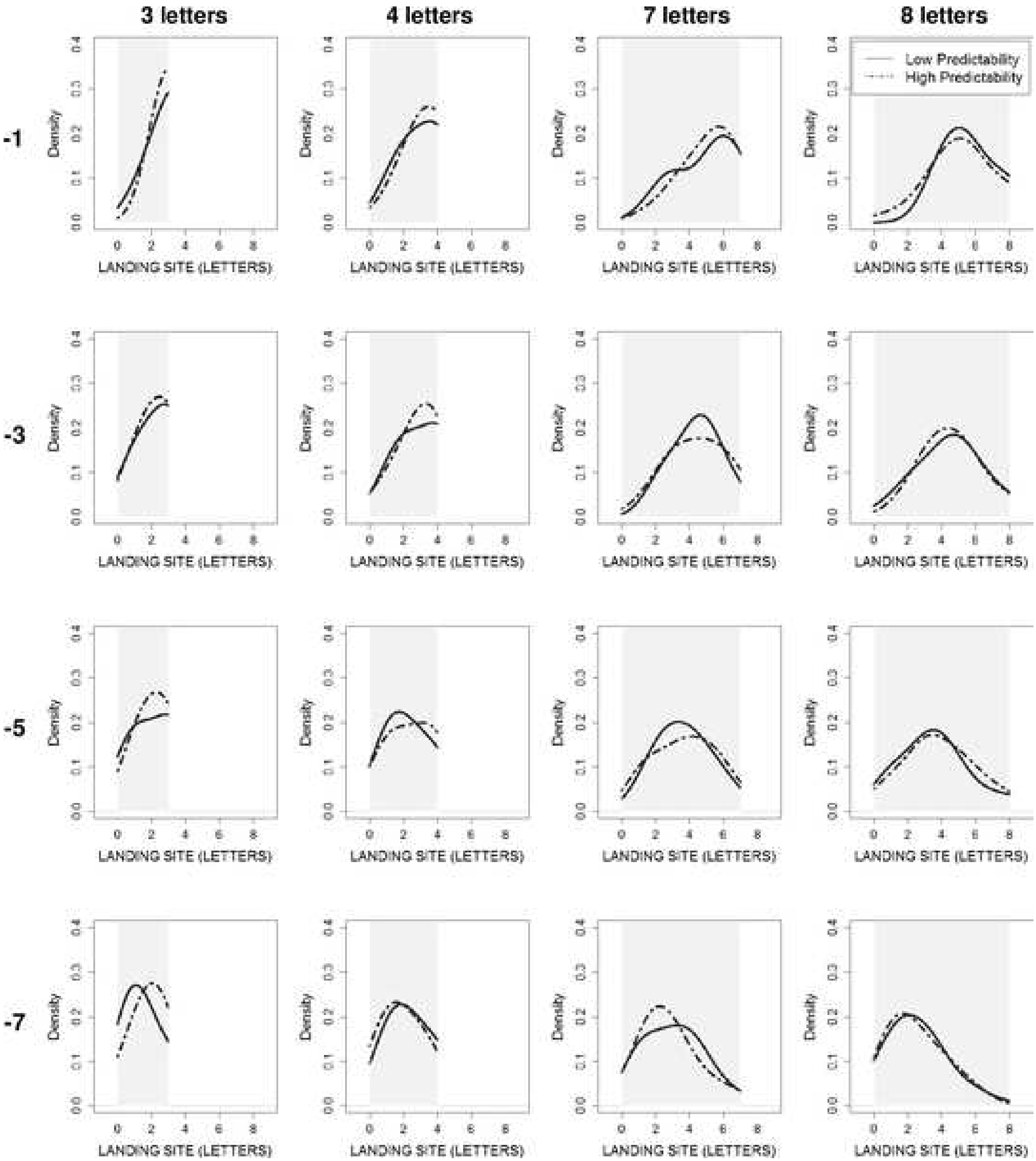

Fig8

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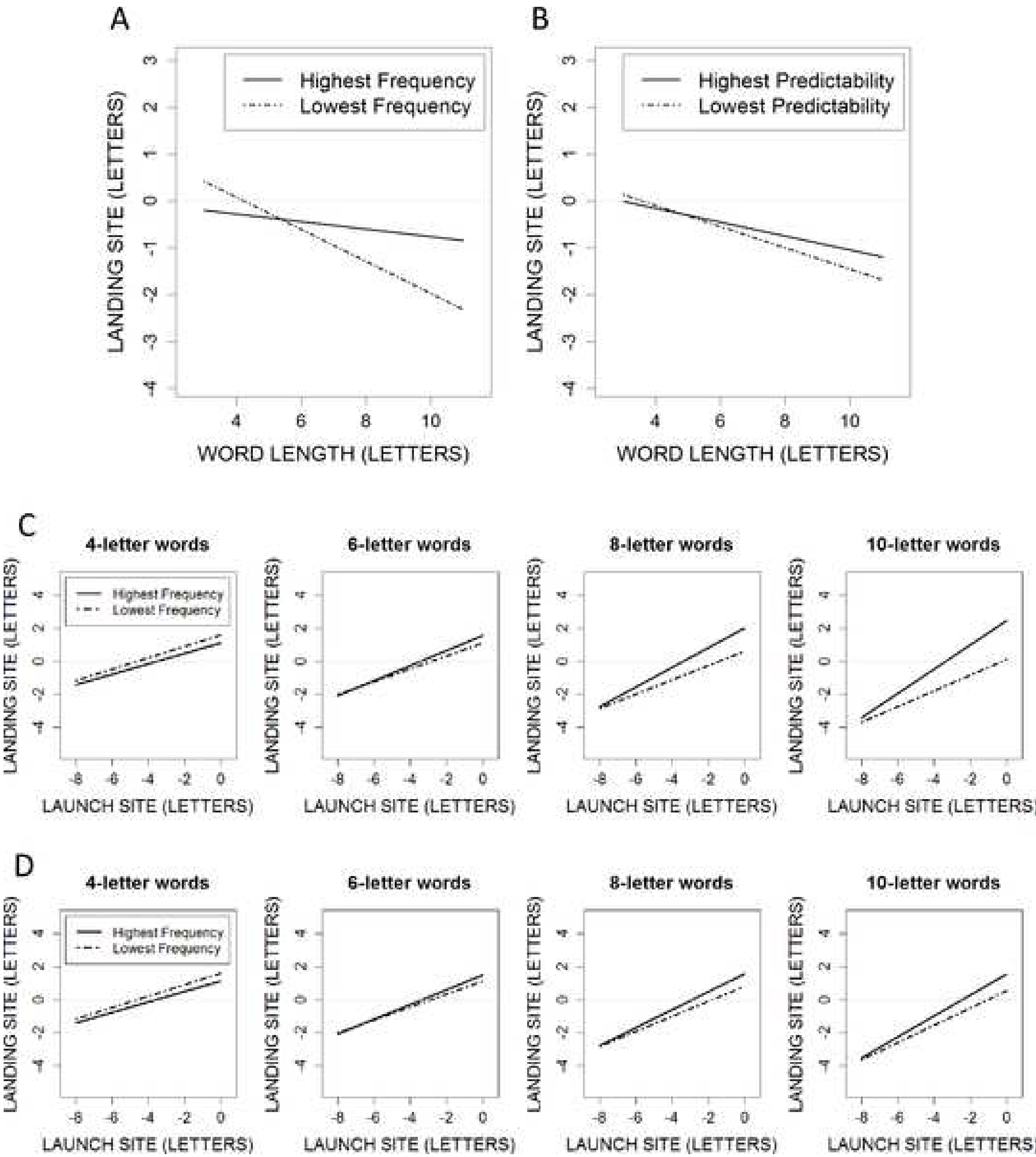

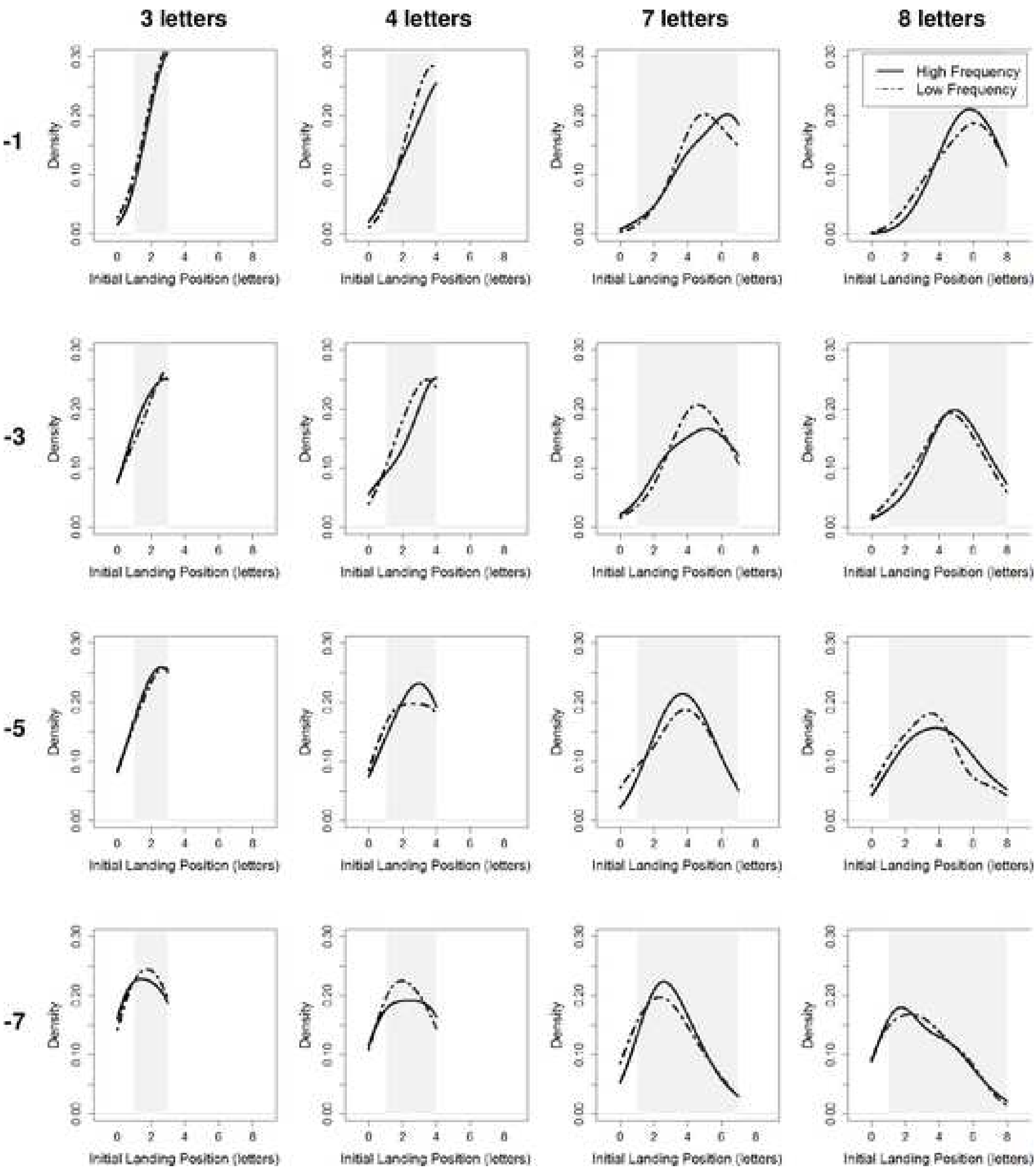
3 letters
4 letters
7 letters
8 letters
-1
-3
-5
-7
High Frequency
Low Frequency
Density
Initial Landing Position (letters)

Fig10

Click here to download Figure Fig10.tif

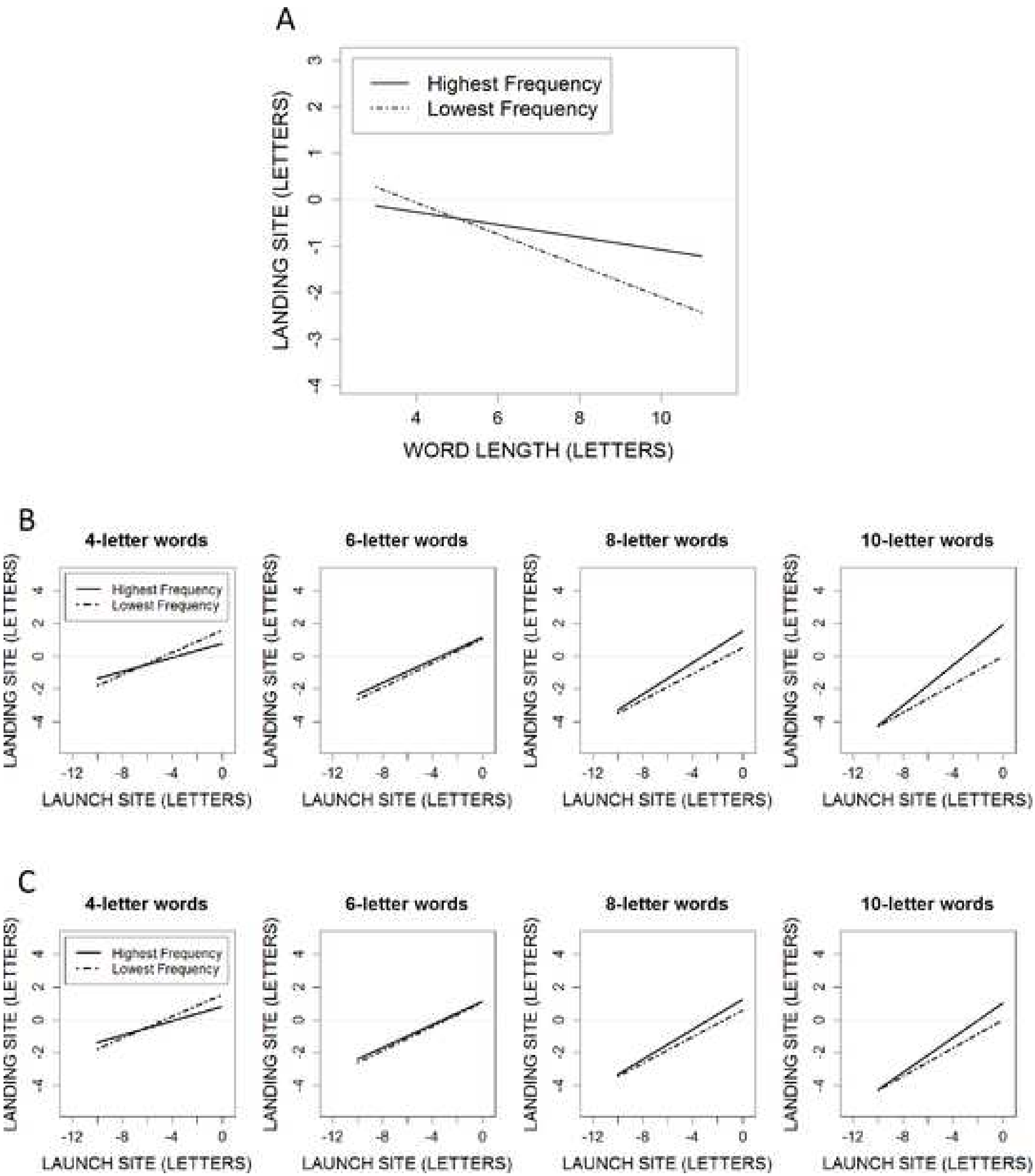

Fig11

Click here to download Figure Fig11.tif

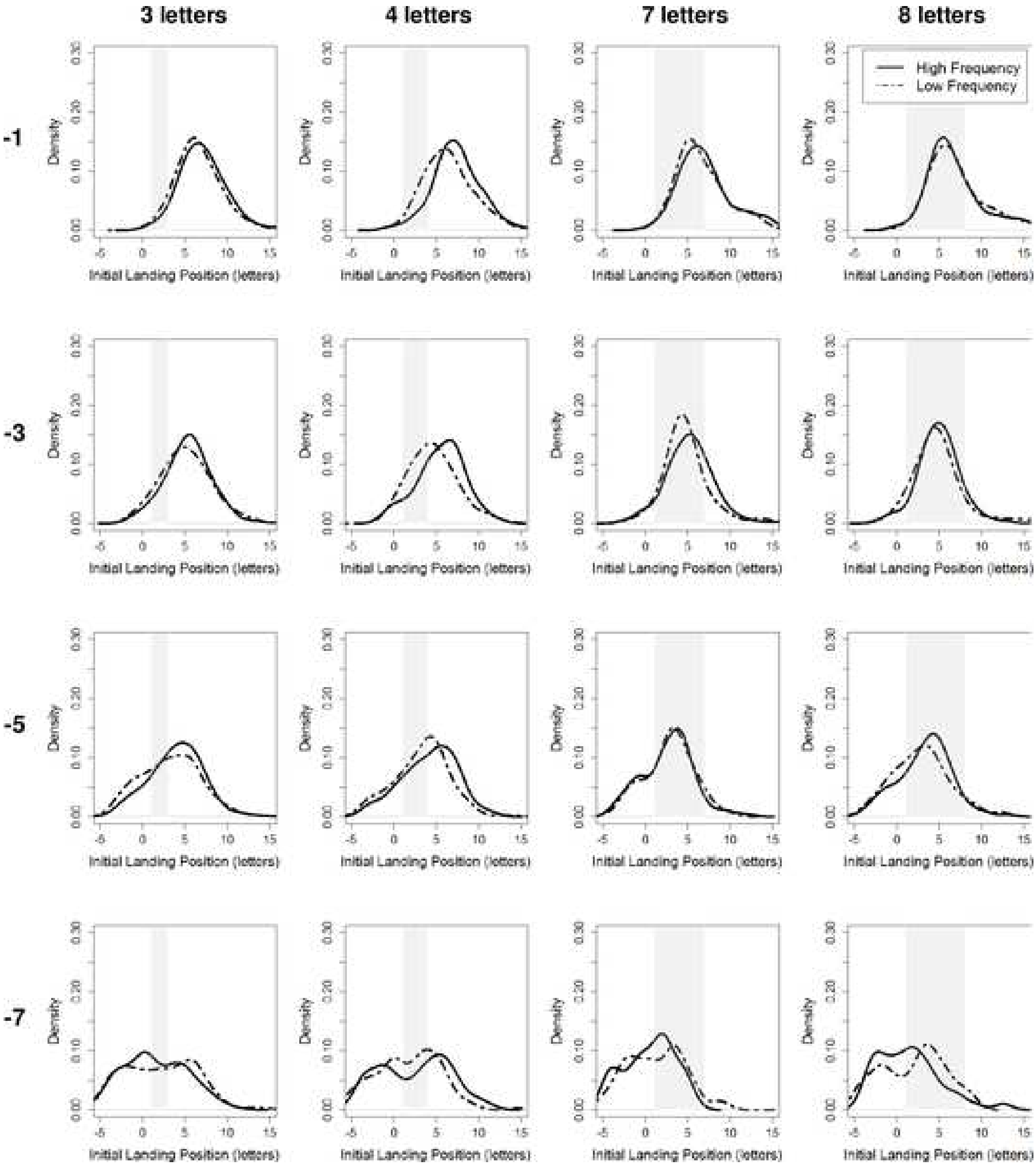

Fig12

Click here to download Figure Fig12.tif