A dynamic adjustment account of word skipping in reading: Evidence from simulations and invisible boundary experiments

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Abstract

Prevalent models of eye movement control in reading of word-spaced orthographies assume a discrete control account to explain word skipping. Accordingly, word skipping results from advanced parafoveal word activation during preview, leading to the selection of word $n+2$ as a saccade target. Consequently, visual and linguistic content of the parafoveal word affect which word is selected as a saccade target. In contrast, according to dynamic adjustment view, saccade lengths in reading are affected by current and next word properties in a continuous manner. First, these predictions were confirmed via simulations for representative models of discrete and dynamic control. Then results of three gaze-contingent invisible boundary experiments studying the visuo-attentional mechanism of skipping are being reported. The results support the dynamic adjustment view by showing a unimodal landing position distribution across a candidate word for skipping and its subsequent word, and that the content of parafoveal word modulates the saccade length only slightly and in a continuous manner. In addition, the location of a visual anomaly within a word had no effect on saccade length, suggesting that parafoveal vision of next word is subject of attention enhancement early enough to affect saccade length computation.

Keywords: word skipping, parafoveal preview, eye movement control in reading

1. Dynamic adjustment account of word skipping in reading: Evidence from simulations and invisible boundary experiments

1.1 Discrete or dynamic adjustment control of saccade lengths?

Despite of considerable differences, prevalent models of eye movement control in reading of word-spaced orthographies (Reichle et al., 1999; Reichle & Sheridan, 2015, Engbert et al., 2005; Risse et al., 2014; Reilly & Radach, 2006; Snell et al., 2018b; see also Brysbaert & Vitu, 1998) share the assumption of a two-stage process concerning the computation of progressive inter-word saccade length: First, lexical processes related to current and upcoming words determine which word will be selected as a target word for a saccade. The saccade is then targeted to the center of the selected word, as the center provides an *optimal viewing position* for parallel letter processing during word recognition (McConkie et al., 1988). This *intended saccade length* is affected by a systematic error towards *preferred saccade length* of seven letters (McConkie et al., 1988). The resulting *saccade range effect* (or systematic error) has been implemented into most computational models, including EZ Reader (Reichle et al., 1999; Reichle & Sheridan, 2015), SWIFT (Engbert et al., 2005; Risse et al., 2014), Glenmore (Reilly & Radach, 2006), and OB1 (Snell et al., 2018b). Finally, *random oculomotor error* proportional to the intended saccade length is added. Due to the initial target word selection -stage, the above depicted traditional view is labelled hereafter as *discrete control* account of saccade length.

However, selecting saccade target word on the basis of lexical information is difficult in comparison to planning saccades on the basis of readily available lower-level information, such as word spaces. First of all, the *vision gradient* (i.e. combination of visual acuity and visual crowding [Bouma, 1970] influences), is the main determinant of saccade lengths as indexed by the effect of word's spatial width on relative landing position, skipping and refixation probabilities (Hautala et al., 2011; Hautala & Loberg, 2015; McDonald, 2006; Hermena et al., 2017). The somewhat blurry *parafoveal preview* may nevertheless activate representations at multiple levels of the cognitive

hierarchy, from the visual to the semantic (Schotter et al., 2012). However, the eyes seem not to wait for the possible activation of high-level representations of previewed word but launch the next saccade primarily contingent on the recognition of the foveal word (for a review, see Schotter et al., 2012; Brothers et al., 2017). This induces a great time pressure for parafoveal activations to affect saccade programming, possibly impeding the readers' ability to make routinely lexical-level skipping decisions.

A logical alternative to the discrete control is a *dynamic control* of saccade length, suggesting that saccade length is dynamically adjusted according to the properties of current and upcoming words. The foundation of a dynamic control lies in the critique of the saccadic range effect (Nuthmann et al., 2016; Cutter et al., 2017). It has been criticized that McConkie et al. (1988) studied only interword saccades from word n to word $n+1$, therefore neglecting the influence of refixations and skipping saccades on the saccade length computation (see Yao-N'Dré et al., 2014). Vitu and colleagues have thoroughly analyzed saccade control in reading including also refixation and skipping saccades by predicting saccade length or landing position with launch distance to next word and its length (Albregues et al., 2019; Yang & Vitu, 2007; Yao-N'Dré et al., 2014). The conclusion that can be drawn from these studies is that readers tend to proceed with much more uniform saccade lengths than what would be expected on the basis of interword saccades only. Moreover, Vitu has argued that saccade lengths are dynamically adjusted, that is, in a continuous manner without the involvement of a target word selection process, even in word-spaced orthographies (Yang & Vitu, 2007). In fact, there is also direct empirical evidence that linguistic properties of upcoming word are used at very least to fine-tune interword saccade lengths also in alphabetic orthographies (Hyönä et al., 2018; Radach et al., 2004; Albregues et al., 2019). Importantly, it should be noted that the dynamic adjustment models already exist for non-spaced orthographies, such as Chinese (for a computational model, see: Liu et al., 2017a-b).

Recently, a novel dynamic adjustment view of eye movement control in reading for word-spaced orthographies was introduced (Cutter et al., 2017, 2018). According to this *center-based saccade length* (CBSL) -account, saccade lengths are computed as follows: First, when previewing upcoming words, the distance between centers of words $n+1$ and $n+2$ are being extracted to represent an optimal length for saccade+2 (a saccade after the next saccade). This preliminary plan is then corrected to some extent by the actual landing position to word $n+1$ (i.e. the launch distance to word $n+2$). Very recently, a computational implementation of the CBSL account was found to provide equal or better fit to empirical word length effects for landing position, skipping and refixation probability measures, relative to a “benchmark” model EZ Reader (Anonymous, preprint; available at: https://osf.io/f6u5p/?view_only=c67ad30e36df4548bf38b80ebcf3de7a). Currently, the CBSL is implemented as a regression model formula¹ given by the Equation 1, which was derived from a linear mixed model fitted to an empirical data, supplemented with an oculomotor error:

$$\text{Saccade length} = 3.8 + 0.53 * CD - 0.018 * CD^2 + 0.27 * LD - 0.026 * LD^2 + \sigma \quad (1)$$

In Equation 1, CD is the distance between the centers of word $n+1$ and $n+2$, and LD launch distance to the beginning of word $n+2$ after landing on the word $n+1$. The oculomotor error σ is identical to the one used in the EZ Reader model, that is Gaussian error with mean of zero and standard deviation increasing by 0.1 letters on the top of 0.5 intercept value for every one-letter increase in intended saccade length, which is the result of the preceding part of the Equation 1.

Effectively, the intercept of the CBSL model (3.8 letters) sets a minimum length for progressive saccades. The CD is the main modulator of saccade length, whereas LD is used to

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¹ As one reviewer noted, a dynamic model needs eventually be expressed as an internal state of the model being updated by some temporal evolution according to an equation of motion.

correct saccade length to some extent according to actualized landing position. This correction is made in order to land on a central viewing position of next word. The non-linear reduction in saccade length at short launch distances (Figure 1) presumably reflects an attempt to prevent coarse skipping of closely positioned next word. This factor may contribute to the reduction in saccade length for skips vs. non-skips documented previously (Krügel & Engbert, 2010; Krügel et al., 2012). Moderate launch distance, on the other hand, may allow maximal saccade lengths because the currently fixated word can still be recognized without a refixation. Similarly, the non-linear effect of CD produces an asymptote preventing the saccade length exceeding general visuo-attentional constraints (Figure 1). See Anonymous (Preprint) for details.

Figure 1.

Estimated Marginal Means of Saccade Lengths from a Linear Mixed Model. Reproduced with permission Anonymous (Preprint).

1.4. Determinants of word skipping.

Considerable amount of research has investigated to which extent skipping depends on the parafoveal processing of next word. To avoid possibly detrimental effects of odd textual information for overall eye movement dynamics, most of these studies have utilized a gaze-contingent boundary paradigm, in which target words are shown with a preview mask disappearing during a saccade that crosses the invisible boundary located at the end of the

preceding word (Choi & Gordon, 2014; Drieghe, 2008; Gordon et al., 2013; Reingold & Rayner, 2006; Plummer & Rayner, 2012).

First, it is well known that the majority of word skipping result from the general oculomotor mechanisms discussed above, pushing the eyes to land just over a short word when launched from nearby (since McConkie et al., 1988, 1989). In addition, skipping is also affected by visual properties of the next word. Depending on their relevancy to the reading task, visually highly anomalous word-objects may be skipped with a very high (Reingold et al., 2016) or low probability (Drieghe, 2008; Gagl et al., 2014). These strong effects provide evidence that at least low-frequency visuospatial information available first in the parafovea, can be used to select saccade targets in reading-like tasks.

Extraction of high-frequency visuospatial information from parafoveal word is compromised due to poor visual acuity. Concerning word skipping, ~5 % effect size has been observed for *faint* font manipulation (Drieghe, 2008; Warrington et al., 2018). In addition, faint font preview did not affect later foveal fixation durations of young readers (Warrington et al., 2018), suggesting that the effects of subtle visual previews may be restricted on the early stages of word recognition (see Reingold & Rayner, 2006).

Concerning linguistic determinants of skipping, according to the review by Brysbaert and Vitu (1998), word frequency affects skipping rates by approximately 5% (e.g., Angele & Rayner, 2013; Angele et al., 2014) and predictability by approximately 8% (Fitzsimmons & Drieghe, 2013; Rayner et al., 2004; Slattery & Yates, 2018). Obstructing parafoveal lexical recognition whatsoever by nonword presentation preserving overall word shape reduces skipping rates approximately 10% (Choi & Gordon, 2014; Drieghe, 2008; Gordon et al., 2013; Plummer & Rayner, 2012). Yet, nonword previews do disturb lexical processing initiated by the parafoveal preview, as evidenced by inflated next fixation durations and regression rates on the target word

(Choi & Gordon, 2014; Drieghe, 2008; Gordon et al., 2013; Reingold & Rayner, 2006; Plummer & Rayner, 2012).

1.5. Discrete or dynamic control of word skipping?

To the best of our knowledge, no convincing evidence for the discrete control view of skipping has been shown in the literature. Note that the studies of Krügel et al. (2010, 2012, 2014) were not informative about the decision process preceding skipping, but were concerned on specifying the differences between skipping and non-skipping saccades while controlling launch distance. In the present study, it was reasoned that discrete control should lead to bimodal distribution of saccade lengths or landing positions corresponding to words $n+1$ and $n+2$ in a situation where skipping is a likely to happen. Simulation with the EZ Reader model (see Anonymous, preprint) confirm this prediction (Figure 2b).²

Instead, according to the CBSL skips are mislocated fixations due to overshooting of a target word. This overshooting has autocorrelative bias because overshooting the center of a preceding word is only partially corrected. Due to lack of saccade target selection processes, the CBSL simulation predict a uniform landing position distribution over words $n+1$ and $n+2$ (Figure 2a).

Figure 2.

Simulated Overall Relative Landing Position Distributions for the (a) CBSL and (b) EZ Reader Models.

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² One reviewer suggested that the bimodality may appear only for certain range of word lengths. We'd like to comment that only short words are typically candidates for skipping and the longer the $T+1$ word, the clearer the bimodality should be.

Note: *Panels A and B*: Landing positions in relation to short target words (≤ 4 letters) that are highly prone to skipping, were simulated with 1000 Monte Carlo runs on a sentence corpus (Schilling, 1998). Values 0-1 represent the target word (T), whereas values larger than 1 represent skipping cases (T+1). To ensure that the preceding word (T-1) was mostly intentionally fixated, it had to contain at least five letters. For providing enough space for the bimodal distribution to appear, the T+1 had to contain at least five letters. As CBSL does not utilize the length of T+1 word in saccade planning, results for this model are given in the scale of T. According to the Hartigan's dip test (Hartigan, 1985) the distribution is unimodal, $D = .0005$, $p = 1$. Instead, EZ Reader results are given in the scale of T and T+1, because either of them may be selected as a saccade target. The distribution is not unimodal, $D = .013$, $p < .001$. Expectedly, the distribution peaks correspond to the centers of the T (0.5) and T+1 (1.5). The sharp peak at value 1.0 most likely reflect mislocated fixations targeted to word T.

According to the discrete control view, linguistic properties of next word directly affect whether it will be skipped or not, as confirmed by the EZ Reader simulation data (Figure 3). The mechanism responsible for skipping in the EZ Reader model (e.g. Reichle et al., 2012) can be summarized as follows: First, high-frequency spatial information from a parafoveal word is extracted fast and in parallel while lexically processing the foveal word. As soon as the foveal word has been recognized, attention shifts to the parafoveal word starting the first stage of lexical processing, the “familiarity check”, consisting of orthographic processing leading to activation of a word form. Skipping occurs if this “familiarity check” completes early enough to cancel the default saccade to the next word – no full recognition of next word is required. Previous simulations have shown that the model produces realistic unique effects of word length, frequency and predictability on skipping rates (Pollatsek et al., 2006), and that the speed of “familiarity check” is the earliest word-content related process which substantially affects saccade lengths (Reichle et al., 2013). Assuming that subtle spatial high-frequency anomalies disrupt letter

encoding, the suspected locus of such manipulation is the “familiarity check”. However, as orthographic processes are not modelled, the model makes no prediction whether a nonword preview or subtle visual anomalies in the previewed word should inhibit skipping more.

Figure 3.

Simulated Word Frequency and Predictability Effects on Relative Landing Position Distributions for the EZ Reader Model.

Note: Relative landing position (RLP) values 0-1 belong to word T and values 1-2 to word T+1. Low foveal load at word T-1 was set by excluding least frequent words (lowest fifth percentile) and to restrict word length to four to seven letters. To restrict the inspection only to a potential skipping situation, word T had maximum of six letters. *Panel B:* The word frequency effect was confounded with the predictability effect. Therefore, highly predictable T words (highest fifth percentile) were excluded. Still, lowest frequency words (fifth percentile, 5% of cases) were predicted to be skipped most (omitted from the figure). Closer inspection revealed that third of these words belonged to the fourth percentile group in predictability, explaining the counterintuitive prediction altogether.

The CBSL model still lacks computational implementation of processes other than those concerned on word length information. However, empirical studies (Hyönä et al., 2018; Radach et al., 2004) suggest only a minor role of other information than word length and launch distance on landing positions. For example, Hyönä et al. (2018) report landing position shifting approximately 0.13 letters to right per one log-unit increase in word frequency, whereas faint font preview reduced progressive saccade length by 0.23 letters in young adult readers (Warrington et al., 2018). On these bases, one may expect small and similar-sized influences for nonword and visual dot previews on saccadic measures.

Finally, the discrete control should be reflected in fixation duration prior to launching a saccade, either due parafoveal-on-foveal effects (Engbert et al., 2005; Risse et al., 2014; Reilly & Radach, 2006; Snell et al., 2018b), or due to extra time required for saccadic reprogramming after skipping decision (Reichle et al., 1999; Reichle & Sheridan, 2015). Empirical results in this respect are mixed as skipping rates seem not to depend on foveal load (Drieghe et al., 2004; Eskenazi & Folk, 2015; Rayner et al., 2011; White, 2007), and fixation duration prior skipping is generally shorter yet may be slightly inflated for infrequent words (Kliegl & Engbert, 2005). However, interactions between launch distance and other independent variables have seldom been studied (White et al., 2005).

1.4. Attentional mechanisms underlying skipping.

A possible yet an unlikely scenario is that skipping is predominantly driven by vision gradient, which mechanism should stress the importance of word beginning information in saccade length modulation. On the other hand, it is well known that covert shift of presaccadic attention provide temporary reduction in the crowding of the target area (for a review, see Li et al., 2016), which explains a large part the preview benefit observed in reading (Briehl & Inhoff, 1995; Johnson et al., 2007; see Schotter et al., 2012). However, presaccadic attention occurs too late to modulate saccade lengths. A form of attention that is more potent to contribute to saccade-length modulation is the early parallel processing of words (Inhoff & Radach, 2014; Inhoff et al., 2005; Snell et al., 2018a, 2019; Wang et al., 2009). This process may explain why skipping is slightly affected by the holistic linguistic properties of words, such as word frequency.

Few studies utilizing invisible boundary paradigm seem particularly informative about the attentional mechanisms involved in skipping. Gagl et al. (2014) found that skipping was inhibited similarly by previews, in which either the beginning or end of a word was subject of clear visual degradation. The manipulation was also associated with inflated foveal fixation durations,

suggesting that the degradation also interfered with higher-level orthographic and lexical processes. Hermena et al. (2016) reported tentative evidence that skipping is insensitive to subtle diacritical marks of the upcoming word in reading Arabic, while the same diacritics resulted in clear preview benefits when the words were later fixated. This finding suggests that the visual information that is available for saccadic modulation is functionally poorer than that later extracted via presaccadic attention. However, skipping rates are generally low in Arabic and also insensitive to parafoveal word frequency, making this complex orthography not an ideal testbed for studying skipping (Hermena et al., 2018).

1.5. The present study

To study whether word skipping is better explained either by the discrete or the dynamic control view or perhaps by the vision gradient, series of gaze-contingent sentence reading experiments with invisible boundary manipulation were run. Skipping was maximized by presenting spatially narrow 3-5 letter (yet unpredictable) target words (Hautala et al., 2011; Hautala & Loberg, 2015; Hermena et al., 2017) surrounded by substantially longer words. This configuration enable testing whether there is a bimodal landing position across word $n+1$ and $n+2$, as predicted by the discrete control, but not by the dynamic adjustment account.

To study which type of parafoveal word information govern the modulation of saccade length leading to word skipping, target words in sentences were previewed either as identical, nonwords or containing subtle visual extra dots located either beginning or end of the item. Here the dynamic and discrete control views differ how they assume information affecting saccades: According to discrete control view, anomalous previews reduce the latter peak of the bimodal landing position distribution. On the basis of previous empirical results, dynamic adjustment should result in leftward shift of the unimodal landing position distribution due to anomalous previews.

Concerning the involvement of attentional mechanisms in skipping, following alternative hypotheses could be stated: If the preview information utilized in saccade length computation is predominantly constrained by the vision gradient, the visual dot located in the beginning part of a word should have a stronger influence on saccade length compared to one in the end part. However, if the early perception of candidate words for skipping is already enhanced by attention, the location of the visual anomaly should not have any effect (Gagl et al., 2014).

Finally, the dynamics of saccade control was studied in a post-hoc analysis. According to the discrete control, the attentional processing of the next word or decision to skip it should be reflected in previous fixation duration especially at short launch distances, because the processing of next word has more likely proceeded to the level of affecting saccade target selection (Reichle & Drieghe, 2013; Schad & Engbert, 2012). If no such interactions are observed, preview exerts an independent influence on saccadic programming, presumably via parallel attention gradient (e.g. Snell et al., 2019). This issue is studied in a post-hoc manner for collapsed data across experiments.

1. Methods

2.1. Simulations.

Because current simulations served to confirm highly expected model predictions, the simulation results were exceptionally reported already in the Introduction. In all of the simulations, the standard Monte-Carlo scheme with 1000 runs was adopted, as used in previous simulation studies of EZ Reader. Specifics of the simulations are being reported elsewhere (Anonymous, preprint; available at: https://osf.io/f6u5p/?view_only=c67ad30e36df4548bf38b80ebcf3de7a). For the CBSL model, data from these previous simulations were used. For the EZ Reader model, an additional

simulation run for the Schilling corpus (Schilling et al., 1998) with the java applet (retrieved from: <http://www.erikdreichle.com/downloads.html>) was needed to produce fixation sequence data required for computing landing positions across two-word sequences reported in Figures 2 and 3. Default parameter values, with no simulation of interword regressions, was applied. The first and last word of each sentence were excluded. Processing and plotting of the simulated data were conducted in the SPSS program. First, the fixation sequence data of all 1000 simulation runs was merged with a corpus key file (containing complete word sequence for all runs), enabling mapping of saccade length and resulting landing position in relation to current, next and its subsequent word. Details of plotting are reported in the notes of the Figures 2 and 3, as well as the statistical test result for bimodality (see also section 2.7.2. Analysis Method).

2.2. Sentence-Reading Experiments 1–3

This research was conducted in three separate experiments with different participants. Regarding the differences between the experiments, only parafoveal preview types and their incidences were modified (Figure 4). The first experiment contained the following four preview conditions (each consisting of 24 target words): 1) In the intact condition, previews were the original words. 2) In the nonword condition, the preview included a nonword formed by replacing a single letter of the target word. 3) In the *dot_begin* condition, the preview target word contained a four-pixel added dot located in the beginning part of the word. 4) In the *dot_end* condition, the preview target word contained a four-pixel added dot located in the latter part of the word. As will be shown, only the nonwords, and not the visual dots, affected the eye movement measurements in Experiment 1, suggesting that the dots were too small to be detected. Therefore, the size of the dots was slightly increased for Experiment 2 (see the Stimuli section), resulting in a decrease in the overall skipping rate and the disappearance of all of the effects between the normal and anomalous preview conditions observed in Experiment 1. The most obvious explanation is that

when 75% of the trials had detectable anomalies, readers adopted a more cautious reading strategy. Therefore, for Experiment 3, we balanced the number of intact (48) and anomalous previews (24 dot_begin, 24 dot_end) by replacing the nonword previews in Experiment 2 with intact previews, resulting in the following preview conditions: 1) intact, 2) large dot_begin, and 3) large dot_end. See Figure 4 for a sample sentence with different previews for a target word.

Figure 4.

Example of a stimulus sentence.

Note: The anomalous previews for target words *ilo* (joy) and *ori* (stallion), are shown in their original size at the top line, and magnified four times in the bottom line. For both of the target words, the two left-most previews are small dots used in Experiment 1, the two middle previews are nonwords (*iio*, *öri*), and the two right-most are large dot previews used in Experiments 2 and 3. The sentence translates as follows: “Matti’s carefully anticipated joy turned out to be premature, as the fast-started stallion suddenly lost its position.”

2.3. Participants

There were 20 native Finnish-speaking participants in each of the three experiments, recruited via student organization mailing lists. The invitation criteria were uncorrected near vision and no reading disability. Table 1 provides descriptive information about the participants for each experiment. The work was conducted in accordance with the APA ethical standards in the treatment of their sample, human or animal, or to describe the details of treatment, World Medical Association Declaration of Helsinki, and the research was approved by the Ethical Committee of the University of Jyväskylä. The participants signed an informed consent form prior to the study,

and they received a movie ticket as a reward for their participation. One participant in each experiment became aware of the preview manipulations.³

Table 1

Descriptive Information of Participants in Each Experiment

		Experiment		
Measure		1	2	3
Gender	(male/females)	3/17	6/14	4/16
Age in years	mean (SD)	25.5 (5.1)	25.6 (4.7)	24.2 (4.4)
Eye dominance	left/right	7/13	8/12	8/12
	mean % (SD)	79 (11)	86 (9)	81 (15)
Comprehension accuracy	min %	58*	71	50*
	max %	92	100	100
Sentence reading time (s)	mean (SD)	6.5 (1.4)	7.0 (1.7)	7.5 (3.1)

Note. *The six low-comprehending participants (< 60% accuracy) nonetheless read the sentences properly, with their mean sentence reading times ranging between 4.9–8.5 seconds.

2.4. Stimuli

Ninety-six spatially narrow nominative target words (e.g., *ilo* [joy] and *tiili* [brick]), containing three to five letters each, were embedded into experimental sentence frames. Nonword previews were constructed by replacing a single letter of a target word with a visually resembling letter of equal width (e.g., *k-h*, *i-l*, *n-u*, *s-o*, *a-ä*) in letter positions 1–3, with the mean position being 1.7. The dot manipulations were drawn manually with image processing software. In the context of a narrow exterior letter, the dot was embedded into a letter space, and in the context of a wide exterior letter, such as *a*, *o*, *u*, or *n*, the dot was embedded inside of the letter. For

³ Exclusion of the manipulation-aware participants did not change the overall pattern of the results, with the exception that the effect of the preview condition on first-pass skipping was no longer significant in Experiment 1 ($p = 0.11$).

Experiments 2 and 3, the size of the dots was increased by adding grey pixels around the black four-pixel dot (Figure 4).

To prevent fatigue, the number of sentences was kept low (48), and every stimulus sentence contained two target words. To prevent skipping due to predictability, the stimulus sentences were designed so that the target word could not be predicted from the earlier sentence context, which was confirmed by a near-zero cloze probability (0.012) of the target words within a sample of six people. To reduce the skipping of surrounding words, the preceding and following words were considerably longer than the target words. Comprehension statements requiring yes-or-no answering by pressing a button, were presented for a random 25% of the sentences. Participants responded to these statements with an 81.4% accuracy rate (Table 1). To engage readers in thorough reading, the statements focused on the meaning of the target words within a sentence. The difficulty is clearly reflected in the low response accuracy. For example, this sentence with the bolded target words—“*According to recent studies, **lice** spread the plague to humans, starting an unfortunate **verse** in the history of humankind*”—was accompanied by this statement—“*The sentence mentioned an insect*”—for which with the average accuracy of the responses was 73%.

2.5. Apparatus

The EyeLink 1000 with tabletop mount (SR Research Ltd. Canada) was used to measure participants' eye movements. The stimuli were shown on an LCD screen (Asus VG-236, 1920 x 1080, 120 Hz, 52 x 29 cm) with a 61 cm viewing distance (one pixel corresponding to 0.2646 mm and 0.02485 visual degrees horizontally). Horizontal eye movements were recorded with a sampling rate of 2000 Hz, and participants' heads were stabilized with chin and forehead rests. Default three-point horizontal calibration covering the entire screen width was conducted prior to

each experiment, with a mean calibration error of 0.14 degrees. The calibration points were presented on the same single line as the experimental sentences.

2.6. Procedure

Eye dominance was determined by the distance hole-in-the-paper test (see Rice et al., 2008), and only the dominant eye was tracked. There were no effects of the tracked eye on the landing position on the target words over the course of the three experiments. Participants whose right eye was tracked launched their saccade toward the target word an average of four pixels farther than the participants whose left eye was tracked. The tracked eye had no interaction with the experimental conditions. Text was shown centered on the screen with proportional Arial 16 point font. The horizontal width of one letter was by average 3.1 millimeters, which corresponds to 0.291 visual degrees and 11.7 pixels at the middle of the screen. The width of a word space was 3 mm. Although some sentences covered almost the entire screen width, the target words were always located within the central 30 degrees of the screen.

To prevent sentence and word properties from producing effects between the four experimental conditions, each target word received every type of parafoveal preview according to a Latin-square rotation of the preview conditions, with the restriction that the same type of preview was not presented for both the first and the second target word in a sentence. In Experiment 3, the nonword conditions in all of the 20 rotations were replaced with intact conditions. Thus, each participant in an experiment received a unique assignment of preview conditions for target words. Two practice trials were presented at the beginning of the experiment, with one of them followed by a comprehension statement. To see a stimulus sentence, participants fixated a circle appearing on the left side of the screen. The fixation was validated by the experimenter by a key press. If the validation was not successful, a recalibration was conducted.⁴

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⁴ One reviewer remarked that the high calibration accuracy may have been compromised to some extent by the usage of lengthy sentences and not employing a 3-point validation before each trial.

After reading the sentence, participants pressed the left mouse button to continue on to the next sentence or to receive a comprehension statement. The participant and the experimenter were situated in separate rooms.

2.7. Eye-movement data processing.

Fixation and saccade data were exported by SR Data Viewer software with a default saccade detection threshold of 30 deg/s. The functioning of the boundary triggers was inspected using the fixation and saccade data. The technical performance of the triggers was acceptable, with an average synchronization delay for screen changes of 6.08 ms, with a 2.3 ms standard deviation. There were only four occurrences with > 10 ms delays in a sample of 10 datasets.

Across the three experiments, out of 5,760 target words presented, there were 5,357 first-pass fixation progressions from T-1 to T or T+1 word. From this data pool, cases with premature trigger firings (1,114) were removed from the analyses of previous fixation duration, first-pass skipping, saccade length, and landing position. These early fires were presumably caused by the maximum sampling rate of 2000 Hz, which we selected to minimize the screen synchronization delay, plus unavoidable hooks (Bahill et al., 1975) and blinks causing momentary deviations in the gaze-position signal. Unfortunately, one target word had erroneous invisible boundary coordinates that always led to premature trigger firing and, thus, the exclusion of this item from the analysis. Luckily, this did not have an effect on the results because the influence of target word identity was controlled by a Latin-square protocol and statistically by a random factor for items. In addition, trigger firing prior to 20 ms of saccade onset was accepted, as changes in visual stimuli after this are unable to cancel the saccadic plan (Buonocore et al., 2015). These early trigger firings occurred equally across different preview types ($\chi^2 = 4.8$, $p = .186$). In addition, for the foveal processing measures (total skipping probability, next fixation duration, and probability of additional fixation), cases (129) of late trigger firing after the beginning of the next fixation were removed

2.7.1. Independent and dependent measures.

For all of the measures, only cases including a first-pass progression from T-1 to T or to T+1 were included in the analyses. *First-pass skip* is a case when a previous fixation was located at T-1 and the next fixation was located at T+1, prior to the fixating of later words in the sentence. *Total skip* is a case when a target word was not fixated at all. *Previous fixation duration* is the duration of a fixation located at T-1 immediately preceding a first-pass skip or a fixation landing on the target word. *Launch distance* is the difference (in pixels) between the previous fixation position and the beginning of a word space preceding the target word, which was also the location of the invisible boundary. *Saccade length* is the difference between the preceding and subsequent fixations in angular degrees. In the *relative landing position* to the target word, values below 1 corresponded to T, and values above 1 to T+1, indicating how far beyond the target word the skipping saccade landed. *Next fixation duration* is the duration of the first fixation on T or T+1. This measure of preview benefit was selected instead of a more commonly used first fixation duration on T, for which high skipping rate lead to low number of observations.⁵ *Additional fixation* on the target word is a combined measure of a refixation on the target word and an immediate regression to the target word after skipping. This measure was used because separate analyses of post-skipping refixation and regression measures would have suffered from reduced power in relation to the skipping probability analyses.

2.7.2. Analysis Method

Eye-movement measures related to the target and the preceding words were analyzed by generalized linear mixed modeling (GLMM) in R using lme4 version 1.1-21 (Bates et al., 2011). Estimated marginal means, pairwise comparisons, and plots were produced by the emmeans-package (Lenth, 2018). Logarithmic transformations were used for gamma-distributed fixation

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⁵ In Experiment 2 where 70% of target words were fixated, there was an expected trend of longer first fixation duration on target word after nonword (222 ms) vs. intact (213 ms) preview, $t = 1.23$, $p = 0.22$.

duration and landing position measures⁶, but not for saccade length measure, which was normally distributed. Experiment-specific analyses were run with one fixed predictor of condition (dot_begin, dot_end, intact, nonword) and two random intercepts for the participant and the item (models with random slopes did not converge). Significant main effects for analysis of variances are followed by pairwise comparisons with Tukey p-value adjustment. Beta estimates are given for the analyses of continuous dependent variables and odds ratios for the analyses of dichotomous variables. An odds ratio is a more intuitive index of effect size, indicating how much more probable an event is in one condition relative to another condition. In the relative landing position analysis of data collapsed across experiments, convergence was obtained for a model with uncorrelated participant and item random slopes, which was achieved using the Afex package (Singmann et al., 2018) for the two-level intact mask factor. Finally, the Hartigan's dip test for unimodality (Hartigan, 1985) was run for the overall landing position distribution, using the diptest R-package (Mächler, 2013).

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⁶ The pattern of significant results was not affected by the logarithmic transformation.

3. Results

Table 2 provides estimated marginal means for the experiment-specific analyses.

Table 2

Estimated Marginal Means Derived from Experiment-Specific Analyses

		Exp 1		Exp 2		Exp 3	
		Mean	SE	Mean	SE	Mean	SE
Saccade Length	intact	2.50	0.07	2.30	0.07	2.47	0.12
	dot_begin	2.58	0.07	2.24	0.07	2.33 ⁱ	0.12
	dot_end	2.52	0.07	2.31	0.07	2.36 ⁱ	0.12
	nonword	2.41 ^b	0.07	2.21	0.07		
First-Pass Skipping Probability	intact	0.42	0.06	0.31	0.05	0.41	0.07
	dot_begin	0.44	0.06	0.26	0.05	0.31 ⁱ	0.07
	dot_end	0.46	0.06	0.32	0.06	0.33 ⁱ	0.07
	nonword	0.35 ^e	0.06	0.29	0.05		
Total Skipping Probability	intact	0.26	0.05	0.14	0.03	0.23	0.05
	dot_begin	0.26	0.05	0.13	0.03	0.17	0.04
	dot_end	0.25	0.05	0.16	0.04	0.18	0.05
	nonword	0.15 ^{i,b,e}	0.03	0.15	0.04		
Previous Fixation Duration	intact	203	6	210	9	211	6
	dot_begin	198	6	214	9	212	7
	dot_end	203	6	213	9	211	7
	nonword	199	6	213	9		
Next Fixation Duration	intact	220	7	213	8	225	5
	dot_begin	212	7	220	8	218	6
	dot_end	214	7	213	8	225	6
	nonword	219	7	215	8		
Additional Fixation Probability	intact	0.06	0.02	0.10	0.03	0.08	0.02
	dot_begin	0.06	0.02	0.06	0.02	0.06	0.02
	dot_end	0.09	0.02	0.07	0.02	0.09	0.03
	nonword	0.12 ^{i,b}	0.03	0.10	0.03		

Note. Index specifies significant contrasts between other conditions indicated by the superscripts ⁱ (= intact), ^b (= dot_begin), and ^e (= dot_end).

3.1. Experiment 1—Small Visual Dots, Intact and Nonword Preview Conditions

After the removal of failed trigger firings, there were 1,486 observations (77.4 % of possible) available for analysis for preview measures (74.3 observations per participant) and 1,456 (75.8%) observations for foveal processing measures.

3.1.1. Saccade length.

The main effect of condition, $\chi^2(3) = 10.26$, $p = 0.002$, was significant, which was the result of a significant contrast between the nonword ($M = 2.41$ deg) and the dot_begin ($M = 2.58$ deg) conditions ($\beta = 0.17$, $SE = 0.05$, $z = 3.18$, $p = .008$). Random effects variances were 0.048 (0.22) for the participant and 0.11 (0.33) for the item.

3.1.2. First-pass skipping probability.

The main effect of condition, $\chi^2(3) = 8.15$, $p = .043$, resulted from the significant contrast between the dot_end ($M = 46\%$) and the nonword ($M = 35\%$) conditions (odds ratio [OR] = 1.58, $SE = 0.27$, $z = 2.73$, $p = 0.032$). Random effects variances were 0.83 (0.91) for the participant and 0.39 (0.63) for the item.

3.1.3. Total skipping probability.

Main effect of condition, $\chi^2(3) = 17.6$, $p < .001$, resulted from the significant contrasts between the dot_begin ($M = 26\%$) and the nonword ($M = 15\%$) conditions ($OR = 2.01$, $SE = 0.38$, $z = 3.26$, $p = .001$), the dot_end ($M = 25\%$) and the nonword conditions ($OR = 1.94$, $SE = 0.37$, $z = 3.45$, $p = .003$), and the intact ($M = 26\%$) and the nonword conditions ($OR = 1.99$, $SE = 0.38$, $z = 3.57$, $p = .002$). Random effects variances were 0.71 (0.84) for the participant and 0.45 (0.67) for the item.

3.1.4. Fixation duration and additional fixation measures.

There were no differences between conditions for previous fixation duration, $\chi^2(3) = 1.53$, $p = .68$, or for next fixation duration, $\chi^2(3) = 2.77$, $p = .43$. For the probability of additional fixation measure, there was a main effect of preview condition, $\chi^2(3) = 10.8$, $p = .013$, resulting

from the significant contrasts between the intact ($M = 6\%$) and the nonword ($M = 12\%$) conditions ($OR = 0.48$, $SE = 0.13$, $z = -2.72$, $p = .033$) and the dot_begin ($M = 6\%$) and the nonword conditions ($OR = 0.48$, $SE = 0.13$, $z = -2.69$, $p = .036$).

3.1.5. Summary.

By selecting spatially narrow yet unpredictable target words, we were able to induce a high first-pass skipping rate of over 40% and a total skipping probability of 25%. Consistently with previous findings (e.g. Gagl et al., 2014), the nonword preview condition led to shorter saccade length and reduced first-pass skipping probability. The size of the nonword preview effect on saccade length was very small, already supporting the dynamic adjustment rather than the discrete control account. As expected, the nonword preview was followed by an increase in the probability of immediate or delayed additional fixation of the target words, indicating disturbed lexical preprocessing. Visual dot preview conditions had no effect on saccadic measures relative to intact condition, suggesting that our visual dots were too small to be perceived during the preview. Therefore, we increased the size of the visual dots for the second experiment.

3.2. Experiment 2—Larger Visual Dots, Intact and Nonword Preview Conditions

After the removal of failed trigger firings, there were 1,408 observations (73.3%) available for the analysis of the preview measures (70.4 observations per participant) and 1,380 observations (71.8%) for the foveal processing measures.

3.2.1. Saccade length.

The main effect of condition was not significant, $\chi^2(3) = 6.48$, $p = 0.09$, nor were planned contrasts. The random effects variances were 0.07 (0.26) for the participant and 0.08 (0.28) for the item.

3.2.2. First-pass skipping probability.

There was no main effect of condition, $\chi^2(3) = 2.96$, $p = 0.39$. The random effects variances were 0.89 (0.94) for the participant and 0.36 (0.60) for the item.

3.2.3. Total skipping probability.

There was no main effect of condition, $\chi^2(3) = 1.40$, $p = .71$. The random effects variances were 1.04 (1.01) for the participant and 0.54 (0.74) for the item.

3.2.4. Fixation duration and additional fixation measures.

There were no differences between conditions for previous fixation duration, $\chi^2(3) = 0.52$, $p = .92$, next fixation duration, $\chi^2(3) = 2.17$, $p = .53$, or the probability of additional fixation measure, $\chi^2(3) = 5.64$, $p = .13$.

3.2.5. Summary.

Increasing the size of the dots abolished all the nonword preview-related effects observed in Experiment 1. The most obvious explanation is that skipping had become a less useful reading strategy when 75% of the trials had effective anomalies. This conclusion was further supported by a significant difference in total skipping probability ($z = -2.17$, $p = 0.03$) between Experiment 1 ($M = 25.5\%$, $SE = 4\%$) and Experiment 2 ($M = 15.1\%$, $SE = 3\%$). To study the hypothesis that large visual dots affect skipping when the probability of intact and manipulated previews are balanced, we replaced the nonword previews with intact previews in Experiment 3.

3.3. Experiment 3—Larger Visual Dots and Intact Preview Conditions

After the removal of failed trigger firings, there were 1,349 observations (70.2%) available for the analysis of preview measures (67.5 observations per participant) and 1,304 (67.9%) observations for the foveal processing measures. All of the intact trials, whose number was now doubled, were included in the analyses.

3.3.1. Saccade length.

The main effect of condition, $\chi^2(2) = 12.07$, $p = 0.002$, resulted from significant contrasts between intact ($M = 2.47$ deg) and dot_begin ($M = 2.33$ deg) conditions ($\beta = 0.15$, $SE = 0.05$, $z =$

3.19, $p = .004$), and intact and dot_end ($M = 2.36$ deg) conditions ($\beta = 0.11$, $SE = 0.05$, $z = 2.33$, $p = .005$). Random effects variances were 0.24 (0.49) for the participant and 0.08 (0.28) for the item.

3.3.2. First-pass skipping probability.

The main effect of condition, $\chi^2(2) = 8.81$, $p = 0.01$, resulted from significant contrast between the intact ($M = 41\%$) and dot_begin ($M = 31\%$) conditions ($OR = 1.50$, $SE = 0.24$, $z = 2.61$, $p = .025$) and from nearly significant intact and dot_end ($M = 33\%$) conditions ($OR = 1.41$, $SE = 0.22$, $z = 2.19$, $p = 0.07$). Random effects variances were 1.40 (1.18) for the participant and 0.29 (0.54) for the item.

3.3.3. Total skipping probability.

The main effect of condition approached significance, $\chi^2(3) = 4.89$, $p = .087$, with non-significant contrasts between the intact and dot_begin conditions ($OR = 1.42$, $SE = .25$, $z = 2.02$, $p = 0.11$) as well as between the intact and dot_end conditions ($OR = 1.30$, $SE = 0.23$, $z = 1.50$, $p = .29$). The random effects variances were 1.35 (1.16) for the participant and 0.22 (0.47) for the item.

3.3.4. Fixation duration and additional fixation measures.

There were no differences between the conditions for previous fixation duration, $\chi^2(3) = 0.95$, $p = .95$, next fixation duration, $\chi^2(3) = 2.17$, $p = .34$, or probability of additional fixation, $\chi^2(3) = 1.27$, $p = .53$.

3.3.5. Summary.

The target words, now shown with enlarged visual dot previews, were less likely to be skipped (41% to 31%), and saccade lengths were shorter than with intact previews. The magnitudes of these effects were comparable to what was observed in Experiment 1. This interpretation was supported by a nonsignificant interaction ($z = -0.19$, $p = 0.98$) between experiments (1, 3) and disruptive preview (Exp 1: nonword, other conditions, Exp 3: intact vs. large dot conditions). However, unlike what was found for nonword previews in Experiment 1,

large visual dot previews in Experiment 3 were associated with neither increased additional fixation probability nor lower total skipping probability relative to intact preview. This result is in line with the previous knowledge of subtle visual manipulations affecting only early word recognition processes, but do not interfere with later lexical processing (Glaholt et al., 2014; Reingold & Rayner, 2006; White & Staub, 2012; Gagl et al., 2014). Again, there were no indications that the location of the dot had any influence on skipping. Thus, it can be concluded that the visual processing of an upcoming short word before skipping is holistic in nature rather than being strongly governed by degrading visual quality toward larger eccentricity.

3.4. Analysis of Saccadic Control Underlying Word Skipping

Experiment-specific analyses indicated that only nonword and large dot previews were effective in affecting saccade lengths and, thus, skipping. To gain more statistical power for studying interactions between factors potentially affecting saccade targeting, data from experiments 1 and 3 were pooled together. Because there were no significant effects of preview type in experiment 2, its data was excluded from this analysis. Then, the disruptive preview types (nonword in Experiments 1, large dot previews in Experiment 3) were collapsed together and compared with ineffective preview types (intact and dot previews in Experiments 1, intact in Experiment 3).

Relative landing position in the scale of target word T was calculated for each fixation preceded by a first-pass saccade crossing the invisible boundary. The landing position was predicted full-factorially with preview (intact, anomalous), launch distance, and previous fixation duration, while random structure included intercepts and slopes for preview type, both for the participants and items. Landing position, previous fixation duration, and launch distance values larger than three SD from the mean were excluded. According to the results, landing position shifts left as a function of increasing launch distance ($\beta = -0.43$, $SE = 0.03$, $t = -13.4$, $p < .001$), as well as after the presentation of an anomalous preview ($\beta = 0.15$, $SE = 0.04$, $t = 3.34$, $p = .002$).

The interaction between launch distance and preview ($\beta = 0.07$, $SE = 0.04$, $t = -1.82$, $p = .070$) was approaching significance, yet the effect is too weak to be interpreted with confidence. The stable influence of preview type, independent from launch distances or previous fixation durations (Figure 5a), suggests that the preview perception-based saccade modulation is not directly dependent on vision gradient or previous fixation duration.

The Hartigan's dip test for unimodality run for the landing positions in intact preview trials indicated that the distribution is strongly unimodal (Figure 5b), and this was true irrespective of the scale used: a) pixel distance to end of target word, $D = 0.0089$, $p = 0.47$, b) scale of target word, $D = 0.0075$, $p = 0.78$, c) combined target (values 0-1) and next word (values 1-2), $D = 0.0075$, $p = 0.78$. Visual inspection of the condition-specific density curves indicate that disruptive previews are associated with higher probability to land on the side of word $n+1$.

Figure 5.

Results of the Saccadic Control Analyses on Relative Landing Position

Note: *Panel (a)*: Estimated marginal means with 95% confidence intervals for a non-significant interaction of launch distance (standardized z-value), previous fixation duration (z-value), and preview type (0 = intact preview, 1 = anomalous preview). The z-values -1, 0, 1 correspond to launch distances of 0.71, 1.41, and 2.13 visual degrees and previous fixation durations of 158 ms, 208 ms, and 276 ms, respectively. *Panel (b)*: Density distribution of relative landing position for different previews in experiments 1 and 3. Values 0–1 on the x-axis belong to target word T and higher values to word T+1, including word space.

4. Discussion

Word skipping has been widely considered as a central phenomenon for the theoretical understanding of eye-movement control in reading (Reichle & Drieghe, 2013). To explain linguistic level effects on word skipping, prevalent models have relied on the discrete control assumption, i.e. the selection of a saccade target word on the basis of parafoveal lexical processing (Engbert et al., 2005; Reichle et al., 1999; Reilly & Radach, 2006; Snell et al., 2018b). In contrast, according to the dynamic adjustment views (Cutter et al., 2017, 2018; Liu et al., 2017a–b), saccade length is computed in a continuous manner as a function of current and next word properties. Here, it was shown by simulations that a prominent discrete control model, EZ Reader, predict bimodal landing position across a candidate word for skipping and its subsequent word, and that linguistic properties of the candidate word affect which one of these words will become the saccade target. Instead, a dynamic adjustment model (CBSL) predicted unimodal landing position distribution, and previous empirical results provided basis to predict small continuous influence of upcoming word on landing position. Finally, the general prediction of attentional involvement in skipping was studied by testing whether the vision gradient over candidate words for skipping is subject of early attentional enhancement capable to affect saccade planning. These predictions were studied in three boundary experiments, in which likely-to-be skipped short target words were shown with varying previews, being either intact, nonword neighbors to target words, or containing an extra visual dot located either in the beginning part or end part of the word. As will be discussed, the results generally favored the dynamic adjustment view over the discrete control explanation.

4.2. Dynamic or Discrete control of Saccades?

Consistent with the CBSL, but not with the EZ Reader prediction, a unimodal landing position distribution was found across target and its subsequent word. This result is in line with previous empirical findings studying landing positions across word spaces (Albregues et al., 2019) and the well-known property of landing position distributions being truncated at word

boundaries (since McConkie et al., 1988, 1989). Neither other signs of discrete control (Engbert et al., 2005; Reichle et al., 2017; Reilly & Radach, 2006; Snell et al., 2018b) were observed: The anomalous previews did not reduce the probability to select word $n+2$ as a saccade target, and the preview effects were not conditional on near launch distance or long previous fixation duration (Eskenazi & Folk, 2015; Rayner et al., 2011; White, 2007). Note that the serial EZ Reader model (Reichle et al., 1999) predict inflated fixation durations prior skipping due to saccadic preplanning, whereas parallel attention models predict that processing of next word may affect fixation duration prior skipping (Engbert et al., 2005; Reilly & Radach, 2006; Snell et al., 2018b). Instead, the present results favor the view that the parafoveal perception induce a time-independent influence on saccade lengths (Schotter et al., 2012; Brothers et al., 2017). However, this aspect of our result should be taken with caution due to reliance of post-hoc data selection procedure of effective and non-effective preview conditions. Taken together, the present results provide support that dynamic adjustment of saccade length is a potent mechanism to explain also word skipping in reading, previously thought to require discrete selection of a target word. In other words, skipping saccades seem not to be categorically different from other progressive saccades.

4.1. The Nature of Parafoveal Preprocessing in Reading.

The possible involvement of attention in saccade length modulation was studied by comparing the effect of location of the visual dot within the preview of the target word; an early attentional mechanism should compensate the degrading vision gradient towards larger eccentricity so that location of the visual dot should not have an effect (see Snell et al., 2019). This hypothesis was clearly confirmed by the results, suggesting that the parafoveal vision is subject to attentional enhancement early enough to affect saccade programming (Inhoff & Radach, 2014; Inhoff et al., 2005; Snell et al., 2018a).

To study which type of parafoveal information is used in saccade length modulation governing skipping, the effects of subtle nonword vs. visual dot previews was compared. Both discrete and dynamics control views predicted that skipping is affected by both types of previews, yet with different targeting mechanism: Dynamic adjustment would lead leftward shift in landing position for anomalous previews, whereas EZ Reader predict reduced probability to target word $n+2$. The results confirmed equal small effect of preview types on saccade length modulation (Choi & Gordon, 2014; Gordon et al., 2013; Plummer & Rayner, 2012; Drieghe, 2008; Warrington et al., 2018). After the already discovered unimodal landing position distribution, it was not surprise that the anomalous previews affected saccade length through the dynamic adjustment mechanism. However, the visual anomalies had to be of sufficient size for being able to affect saccadic length, which seems to parallel Hermena et al. (2018) finding no skipping effects for the absence of small diacritic marks in the reading of Arabic. Together, the available evidence suggests that any detectable information in blurred parafoveal vision is used to guide saccades in reading. Tentatively, according to predictive coding framework (for a review, see Huang & Rao, 2011), a preview may first induce a visual-orthographic prediction, which need to be yet confirmed on the basis of more acuity vision (Friston et al., 2012). Any detected oddity in preview may intervene the prediction generation and reduce the saccade length to some extent. Instead, highly familiar preview induces fast and reliable predictions, and lower quality visual sample may be sufficient to confirm their accuracy.

4.1. The Cognitive Mechanism Underlying Word Skipping in Reading.

Combining the present findings with the previous knowledge of the importance of spatial width of current (Cutter et al., 2017; 2018) and next word (Hautala et al., 2011; Hautala & Loberg, 2015; Hermena et al., 2017) on saccadic measures, a following dynamic adjustment mechanism for skipping can be drafted: First, as explicated by the CBSL account (Cutter et al., 2017, 2018;

Anonymous, preprint), the preliminary saccade length is extracted through preview of distance between center of words $n+1$ and $n+2$. Then, this preliminary program is corrected to some extent by the actual launch distance from word $n+1$ to word $n+2$. The results of the present study then add to this knowledge by showing that the saccade length is also fine-tuned by the preview processing of the next word. This preview processing seems to be enhanced by parallel attention gradient, instead of being fully determined by vision gradient (Gagl et al., 2014). If this preview processing does not encounter anything highly anomalous content (Reingold et al., 2016), its influence on saccade length is rather small, yet sufficient to produce the small visual and linguistic level effects on word skipping. Together these mechanisms produce uniform landing position distribution across words $n+1$ and $n+2$.

Previous studies have compared and modelled landing positions of skipping and non-skipping cases (Krügel et al., 2010; Krügel et al., 2014). Such a comparison is based on discrete control assumption, but from the perspective of dynamic adjustment it would mean comparing beginning of a distribution with its tail. Nevertheless, skipping saccades are special for the reason that two word spaces are crossed, which reduce saccade length (Krügel et al., 2010) and increase oculomotor error (Krügel & Engbert, 2014). At least the former effect is fully in line with the current computational model of CBSL through the non-linear effect of launch distance (see Figure 1).

4.3. Preview Effects on Later Foveal Processing.

After fixing the saccadic program, the processing of a parafoveal word continues, and its visual perception is further enhanced by the presaccadic attention mechanism (Li et al., 2016; Rolfs & Carrasco, 2012). In line with previous studies utilizing faint font manipulation (Glaholt et al., 2014; Reingold & Rayner, 2006; Warrington et al., 2018; White & Staub, 2012), but in contrast to partial visual degradation manipulations (Gagl et al., 2014), our subtle visual dot

preview was not associated with foveal processing difficulties. Thus, the task-irrelevant visual dots affected only early level of lexical processing of words, which was overcome rapidly during later foveal processing (Warrington et al., 2018).

As expected, orthographically illegal previews led to later foveal processing difficulties, which has been observed in several previous studies (Choi & Gordon, 2014; Gordon et al., 2013; Hohenstein & Kliegl, 2014; Schotter et al., 2018, 2019; Plummer & Rayner, 2012; Reingold & Rayner, 2006). Surprisingly, the effect of nonword preview did not yet manifest in the next fixation duration (on T or including also T+1 word), but appeared first in the increased probability to make an immediate additional fixation and in later regressions to the target word. A contributing factor here was the use of visually similar replacement letters, which are known to reduce the effect of nonword preview on foveal measures (Marcet & Perea, 2018). Also, the present study was not optimized for studying foveal effects due to high skipping rate, which reduced the number of first-pass fixations. In line with this explanation, there was a trend towards expected direction in the first fixation duration of target words in experiment 2, where the skipping rate was lowest.

4.4. Limitations.

It is possible that the discrete control disputed herein depends largely on the distinctiveness of preview objects controlling the speed and the certainty of parafoveal perception. Supporting evidence for this view is provided by Reingold and colleagues (2016), who showed that symbol strings unrelated to the text are highly likely to be skipped during reading. Thus, the caveat with visual manipulations is that in some circumstances, they may become saccade targets (or non-targets) themselves. We did not find such an effect; yet, in Experiment 2, there was a trend toward longer saccade lengths when the anomalous dot was in the end rather than in the beginning part of a word. Given that the nonword effect was also absent from Experiment 2, it is possible that when

almost every sentence contains something weird, readers start to invest their attentional resources in detecting these anomalies by trying to fixate every word (see Wotschack, & Kliegl, 2013, for the strategic control of skipping). Thus, it is recommended that the number of intact and visually anomalous trials should be balanced in this type of research.

Importantly, the present findings may be rather specific to short words and therefore likely to represent skipping driven by the visuo-oculomotor mechanism. Instead, the skipping of longer words is likely to be driven more by higher-level cognitive processes, perhaps by a genuine discrete control mechanism taking place in rare occasions. In fact, there is evidence that word predictability has an equal influence on word skipping in short and long words (Rayner et al., 2011), meaning that the effect is relatively greater in long than short words. Moreover, readers can also strategically adjust their reading, e.g., by skimming parts of a text or skipping redundant words or entire parts of sentences.

Methodological particularities of the present study include insertion of two target words into a single sentence, which lead to long carrier sentences. Despite of high calibration accuracy values, the long sentences may have induced some extra head movements. The comprehension questions tried to guide attention towards target words, being therefore often concerned on minor details. Consequently, few participants scored low in these questions, making it somewhat unsure if they were fully engaged with reading all of the time. However, their data was kept in the analyses because exclusion of any participant would have produced a bias in the latin-square rotation of conditions.

4.5. Conclusions.

The present findings provide clear support for the dynamic adjustment view of saccade length also in word-spaced orthographies (Cutter et al., 2017, 2018; Anonymous, Preprint), as previously studied in non-spaced orthography (Liu et al., 2017a–b, 2018). The dynamic center-

based saccade length model (Cutter et al., 2017, 2018; Anonymous, Preprint) supplemented with empirical knowledge, was found to provide a highly tenable and parsimonious account of eye movement control underlying word skipping. Boundary manipulations provided also novel evidence that attentional enhancement of vision over short next word takes place early enough to affect fine-tuning of saccadic length. It can be concluded that dynamic adjustment control provides a viable alternative to discrete control family of models, which assume that saccade target word selection is driven by lexical processes.

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Appendix A.

Stimulus sentences. Target words are bolded for illustration.

Practise 1: Loppujen lopuksi olen varsin tyytyväinen uuteen polkupyörääni, vaikka siinä olikin aluksi pikkuvikoja.

Practise 2: Vuosien pohdinnan tuloksena olemme viimein päättäneet muuttaa kaupungin vilksestä maaseudun rauhaan.

Luullakseni minulle osoitettu **tili** kerryttää korkotuloja, vaikka odotettavissa oleva tuotto jäänee **liki** olemattomaksi.

Matin tarkoin ennakoima **ilo** osoittautui ennenaikaiseksi, sillä vauhdikkaasti aloittanut **ori** menetti asemiaan yllättäen.

Pekan huolellisesti esittämä **iva** unohdettiin, sillä yleisössä vallitsivat **eri** näkemykset aiheesta.

Vahvoista epäilyksistä huolimatta **tie** johdattaisi meidät perille, sillä tunnistamani **lila** rakennus sijaitsi sen varrella.

Suomessa harvoin esiintyvä **koi** tuottaa päänvaivaa, etenkin jos tämän kauniin luontokappaleen **aie** suuntautuu vaatekaappiin.

Alun tappioasemastaan huolimatta **itä** kukisti lännen tässä pesäpallon **iäti** kestäneessä perinnekeppailussa.

Läheisestä kaupasta ostamani **tilli** saattoi olla vanhentunut, mutta keittoon lisäämäni **luu** ostettiin kyllä varmasti tuoreena.

Viimeaikaisten tutkimusten mukaan **täi** aiheutti ruton leviämisen ihmisiin, jonka seurauksena alkoi harmittava **jae** ihmiskunnan historiassa.

Tässä tilanteessa etenemme **ovi** kerrallaan toivoen, että jokin niistä olisi jätetty **irti** saranoistaan vaikka epähuomiossa.

Martin selvitystyön perusteella **laji** näyttäisi leviävän nopeasti kohti pohjoista, vaikka kyseinen **hai** viihtyy edelleen myös lämpimissä vesissä.

Äänekäästä karjaisusta huolimatta **tilli** vaikutti kestäväen karatekan hyökkäyksen, vaikka hänen lyöntinsä **yty** saavutti ennätysvoiman.

Kaikista tunnetuista tekijöistä **ikä** määrittää vahvimmin henkilön kykyä välttää **oja** tavallisessa maantieajossa.

Sattumalta löydetty **tila** vaikutti sopivan asiakkaalle, jonka seurassa kulkenut **isä** osoittautui huumorimieheksi.

Yleisön suureksi yllätykseksi **kiri** irtosi ikämieheltä kuin nuorelta pojalta, joskin hänen esittämänsä **villi** vauhdinpito jäi kovin lyhytaikaiseksi.

Pieneliöiden sankoin joukoin erittämä **tali** liukasti rantakiven, mikä oli näin jälkiviisaasti ajateltuna **tae** onnettomuuden sattumiselle.

Useamman tarkastuksen jälkeen **rivi** osoittautui lottovoitoksi, ja nyt oli vain varmistettava ettei esimerkiksi **tuli** tuhoaisi käsissäni olevaa aarretta.

Joudumme toteamaan ettei edes neuvokas **äly** mahdollista kaikkien ongelmien ratkaisua, minkä ajatuksen viimeinen **dia** esitti vaikuttaneelle yleisölle.

Kaiken kaikkiaan **ajo** pohjoisen laskettelukeskukseen tuntui Piiasta lyhyeltä, johon osaltaan vaikutti leppoisa **uni** kesken automatkan.

Raimoa alkoi kovasti kiinnostamaan **ujo** naapurintyttö, jonka tahattomasti esittämä **ele** saattoi tarkoittaa kiinnostuksen olevan molemmipuolista.

Nopealla aikataululla alkanut **ale** saavutti suuren suosion, vaikka kaikkien haluama **liivi** loppuikin varastosta.

Keväisen uutisen mukaan **kyy** heräilee pesistään, ja nisäkkäistä ainakin **siili** käyttää ravinnokseen käärmeitä.

Toiveitteni mukaisesti **ilta** jatkui rauhallisissa merkeissä, vaikka taustalla vaikuttava **työ** mietitytti varmasti osallistujia.

Toisinaan kokemani **olo** liittyy jotenkin siihen näyttääkö **iho** punoittavan käsissäni.

Laskelmien mukaan ilmoitettu **ala** oikeuttaa maataloustukiin, mutta korvauksen lopullinen määrä riippuu kuinka **keli** kohtelee viljelystä.

Kokemusteni mukaan **jää** vaikuttaa usein vahvemmalta kuin se onkaan, mistä jään pinnalle kertynyt **utu** toimikoon varoitusmerkkinä.

Juhlissa nauttimani **silli** osoittautui mainioksi herkuksi, eikä runsaasti nauttimani **tee** maistunut pahalta sekään.

Vaikka kilpailijan **ote** vaikutti lipsuvan riuhtaisuun aikana, mittaustuloksen mukaan **kivi** laskeutui ennätystulokseen.

Muistathan, että tarjoamasi **syli** vaikuttaa lapsesi hyvinvointiin pitkälle aikuisuuteen ollen hänelle suunnaton **etu** elämän polulla.

Kerrohan minulle **syy** eroosi pitkäaikaisesta kumppanistasi, jokin muukin kuin sinun pitkäksi venynyt **ura** jääkiekkoilijana.

Harvoin tapaamani **täti** soitti tänään minulle ilmoittaen, että hänen kadonnut **veli** löytyi hyvässä kunnossa asunnostaan.

Tämä ensimmäistä kertaa maistamani **rae** vaikuttaa varsin onnistuneelta pääsiäiskarkilta, mutta sen mukana tullut **kori** kaipaisi kehittelyä.

Tarkemmissa tutkimuksissa **tyvi** paljastui murtuneeksi, vaikka erikoisvalmisteinen **hiili** tiedetään erittäin lujaksi materiaaliksi.

Ahkeruudestani huolimatta **vyö** puristaa edelleen vatsaani, joten en tiedä millä keinoin merkittävä **lovi** painostani vähennetään.

Viime viikon keskiviikkona **vilu** valtasi kehoni kuumeen noustessa äkillisesti, kun taas perjantaiyönä **hiki** kasteli sänkyni kuumeen laskiessa.

Etäällä näkynyt **väli** mitattiin riittävän leveäksi mittalaitteella, joka vaikutti olevan **lelu** ammattilaisen muiden laitteiden rinnalla.

Ohjelmassa on mielestäni aika nostaa **lasi** vastavalmistuneiden kunniaksi, ja karauttaa ilmoille **säe** tunnettua sävelmää.

Reseptin mukaisesti **riisi** keitettiin kypsäksi kattilassa, johon mahtui suunnilleen **kilo** valmista puuroa.

Kesän tunnusomaisiin tuoksuihin kuuluva **piki** kuvastaa sitä tarmoa, jolla Suomessa pidetään **yllä** tiestön kuntoa.

Päivänsankarin harmiksi paperinen **pilli** pehmeni hetkessä, jolloin voimakas **imu** tukkeutti putken kokonaan.

Tuntemattoman henkilön **tyly** käyttäytyminen herätti huomiota siinä määrin, että jotkut mainitsivat hänet **ilmi** kauppakeskuksen vartijalle.

Varovasti käsitelty **öljy** läikähti yli astiansa, minkä seurauksena **talli** jouduttiin väliaikaisesti sulkemaan.

Selvitystyösi perusteella **laki** mahdollistaa esitetyn veroratkaisun, vaikka kyseessä olisi moraalisesti arveluttava **peli** nykyisessä asenneilmastossa.

On hankala arvioida riittääkö **sali** osallistujille, joten kokouksessa käytettiin **tovi** asian pohtimiseksi.

Neiti Makkosen viimekertainen **sija** oikeutti viidenteen lähtöruutuun, mistä osoituksena oli nimetty **viiri** lähtöruudun vieressä.

Unelmieni tontilla **joki** virtaisi takapihallani, jota pitkin **lohi** vaeltaisi kutemaan.

Epäselväksi jäi minkäläinen **olio** takapihalla oli liikunut, mutta ainakin sen jättämä **lajä** siivottiin pois.

Kalastusverkkoon takertunut **kita** irrotettiin hellävaraisesti, mikä oli välttämätön **apu** pahoin kärsineelle eläimelle.

Dokumentissa näytetty **akti** analysoitiin tarkoin **läpi** viikon kestäneen konferenssin aikana.

Silloin tällöin näkynyt **kuu** valaisi maastoa, ja heidän jaloissaan **suo** tuntui pehmeältä patjalta.

Uskomattoman maukas **liha** huipensi grillijuhlat, ja ihmiset tuntuivatkin keskustelevan **suu** täynnä ruokaa