Proficient readers skip more words: examining to what extent EZ-Reader accounts for reader skill modulation of skipping rates

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Abstract: Readers skip about 20-30% of the words they read (Rayner, 2009; Schotter et al., 2012). Due to having better lexical representations of words, better readers are thought to skip words more frequently than worse readers (Eskenazi & Folk, 2015). In this paper, a literature review is made of this hypothesis, looking at what influences skipping rates, and how reader skill could modulate this. Then EZ-Reader is explained, a mathematical model that models human reading behavior (Reichle et al., 2003). Subsequently, this model is used to run simulations on the GECO corpus (Cop et al., 2016), where simulation results are compared with empirical results for monolinguals (high-skill readers) and bilinguals (low-skill readers). Measures were taken of the total skipping rate and skipping rates for both low- and high-frequency words. There are conclusive findings that EZ-Reader can not account for reader skill modulation of skipping rates in the current implementation. Low-frequency skipping rates are predicted to be much higher than the empirical results for low-skill readers. The implications of these results are discussed, as well as their relevance towards AI.

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1 Introduction

Due to eye-tracking technology, researchers have been able to study the behavior of the eyes during reading. How they move during reading is very systematic. Even to such an extent that predictions can be made on where regressions are made, or where readers slow down, within a text. Thanks to significant improvements in technology, and due to sophisticated models, steps can be taken to increase the knowledge on how humans read and what processes are associated with them.

Studying eye movements is important because from eye movements, cognitive processes can be inferred (Rayner, 1998). The study of eye tracking is a proven, non-intrusive method of examining how the human mind works. According to Radach and Kennedy (2004), there are three theoretical perspectives regarding the inferring of cognitive processes through the study of eye movements. First, the examination of perception and motor control is theoretically possible through eye-tracking studies. However this is more of a theoretical possibility, rather than a conventional way of research (Radach & Kennedy, 2004). A second possibility is the study of information acquisition where reading is on the same processing level as the processing of a pictorial scene (Radach & Kennedy, 2004). Here, the main debate is that of serial vs. parallel processing of information (Rayner et al., 2003). Thirdly, Radach and Kennedy argue that this research can be used for the development, and testing, of psycholinguistic hypotheses about language processing. It must be noted that these three theoretical perspectives have a lot in common, where computational models like EZ-Reader (Reichle, Rayner & Pollatsek 2003) and Swift (Richer, Engbert & Kliegl, 2006) have incorporated parts of these three theoretical perspectives. Yet, there is another application for eye-tracking studies, as Shaik and Zee (2017) argue that they facilitate the diagnosis of complex neurological problems and are a tool for assessing brain functions.

This thesis will discuss the EZ-Reader model. EZ-Reader is seen as the most influential eye movement model because it accounts for all of the required benchmark data and makes unique predictions (Hyönä & Kaakinen, 2019; Rayner, 2009). Additionally, EZ-Reader is an open source project and is used in a lot of research to run simulations on (Reichle et al., 2009; Reichle et al., 2013; Reichle et al., 2012; Staub, 2011; Mancheva et al., 2015; Eskenazi & Folk, 2015). Models like EZ-Reader have furthered the knowledge on eye movements in a way that was not possible with solely empirical research. As pointed out by Reichle and Sheridan (2015), EZ-Reader provides a simple theoretical framework that encapsulates eye movement control during reading. Additionally, models like EZ-Reader can for instance help in explaining counter-intuitive findings, which are usually hard to account for in empirical studies. An instance of this has been documented by Nuthmann, Engbert and Kliegl (2007).

In the past few years, a lot of research has been done on the processes behind the skipping phenomenon during reading. About 30% of the words are not fixated when humans read (Rayner, 2009; Schotter, Angele, & Rayner, 2012). What influences skipping is a big theme in current research, evident from the amount of research done on this topic in the last two decades (Fitzsimmons & Drieghe, 2011; Drieghe et al., 2004; Slattery & Yates, 2018; Kliegl

& Engbert, 2005; Eskenazi & Folk, 2015; Drieghe et al., 2019; Veldre et al., 2020). Therefore it is interesting to examine what EZ-Reader predicts with regards to skipping, and what the implications of it are. Because there are a huge amount of factors that impact skipping rates, the research is narrowed down to a specific topic. Multiple authors note that language comprehension (i.e. how well do you understand the language) is a modulator of skipping rates (Eskenazi & Folk, 2015; Veldre & Andrews, 2016, 2017, 2018a, 2018b, 2018c; Veldre, Reichle, Wong & Andrews, 2020). Good comprehenders can read and write well while bad comprehension leads to lesser writing and reading skills. How exactly they influence skipping rates is interesting, and especially how well EZ-Reader accounts for this phenomenon. Thus, the research question is as follows:

Can EZ-Reader account for skipping rates modulated by language comprehension in its current implementation?

In order to answer this question, first a theoretical background is given, where commonly used definitions are explained, together with a review of the mechanisms that influence skipping rates in reading. Then a description of EZ-Reader and its implementation is given. Simulations are run over a text corpus and the results are compared with empirical results. Ultimately the predictions made by EZ-Reader are compared to the empirical data, whilst also checking if the predictions match the expected predictions from the literature.

2 Relevance towards AI

Within Artificial Intelligence, the goal is to successfully model human behavior. Cognitive studies are very important to this extent, as from these studies a lot can be learnt about human behavior. One of the main studies on human cognition is that of eye-tracking studies. Since the 21st century mathematical models about reading have been developed and are now a source of theoretical innovation about human cognition and behavior (Reichle & Sheridan, 2015). Thus gaining more insights into how humans read will help facilitate modeling human behavior in general, so that eventually an accurate AI model can be created.

EZ-Reader tries to capture human eye movements during reading. This thesis evaluates to what extent EZ-Reader can effectively account for empirical skipping rates found for monolinguals (high-skill readers) and bilinguals (low-skill readers). This distinction has not been evaluated earlier for skipping rates. Hence this study will be able to provide additional information about EZ-Reader’s fit which will eventually lead to a better understanding about how humans read.

3 Theoretical background

First, a brief overview is given on the relevant eye movements during reading to serve as background material. Then, recent findings from studies with implications for the skipping mechanism during reading are discussed.

Eye movements in a text are typically short and rapid movements, called saccades (Erdmann & Dodge, 1898; Huey 1908). Nearly no information is obtained during these movements. When a saccade goes in a backwards direction, it is called a regression. Fixations are the moments between saccades where the eyes stay stationary for a brief period of time. Computational models like EZ-Reader try to capture these eye movements as accurately as possible. In order to do so, these models have to make predictions about common eye-movement measures. These measures are across-subject averages for how long and how often words are fixated. Three measures are standard: gaze duration, first-fixation duration and single-fixation duration (Liversedge & Findlay 2000; Rayner 1998). Gaze duration is the total of all fixations on a word, before the eye focus has left the word. First-fixation duration is the time spent on the first fixation of a word and single-fixation duration is the average time spent on fixating words that are fixated just once during first pass reading. During a fixation, visual information is obtained from the text (Erdmann & Dodge, 1898; Huey 1908). The information extracted is only done over a space of 3-4 letter spaces from the left of a fixation, and 14-15 letter spaces to the right (McConkie & Rayner, 1975; Rayner, 2009), this is the so-called perceptual span. Most of the identification of words is done within the fovea (the 2 degrees in the center of the vision), with word processing also being possible in the parafovea which is the area surrounding the fovea. From pre-processing of the parafovea, parafoveal-on-foveal effects arise which include the shorter fixations of the next word, or even skipping of word n+1.

3.1 Factors influencing skipping rate

These parafoveal-on-foveal effects have been documented to be quite influential for skipping during reading. Commonly used indicators of skipping probability are word frequency (how often a word occurs within a text) (Rayner et al., 2003; Richter, Kliegl, 2006) and word length (Rayner, Reichle & Pollatsek, 2003, Slattery & Yates, 2018). It is commonly reported that the shorter and more frequent a word is, it is more likely to be skipped. Cloze probability (the probability that the target word completes a sentence based on the preceding context) is also accounted for within the EZ-Reader model as an influencer on skipping rates, as well as systematic error in the programming and execution of saccades (Rayner et al., 2003). Additionally, Brysbaert, Drieghe and Vitu (2005) found that the distance between a parafoveal word relative to the fixation location (a.k.a. the launch site) also influences skipping rates. The distance between the launch site and word n+1 is influential because the visual acuity decreases when a word is further within the parafovea (Bouma, 1978; Brysbaert et al., 2005), meaning that words closer to the fixation are easier to identify parafoveally, and thus easier to skip. Empirical data backs this up, as Brysbaert and Mitchell (1996) found that word length and relative distance between fixation and word are a factor. Table 1 shows some notable results. Moreover, McConkie et al. (1994, 2001) found that the probability of word skipping is predictable when using just word length and launch site as parameters.

Table 1: The skipping probability with regards to word length (wl) and launch site (ls) (see Brysbaert & Mitchell, 1996, experiment 3).

	2-word length	3-word length	4-word length	8-word length
-1 launch site	0.84	0.80	0.78	0.28
-3 launch site	0.81	0.75	0.58	0.17
-7 launch site	0.63	0.50	0.28	0.01

Novel research by Veldre, Reichle, Wong and Andrews (2020) reported another strong effect on word skipping, called the plausibility-preview effect. This research built further on research by Veldre and Andrews (2016, 2017, 2018a, 2018b, 2018c) who found that readers had a lower probability of skipping a semantically or syntactically incorrect word (Veldre & Andrews, 2018a). Participants would read 80 sentences for comprehension, whilst the eyes were being tracked. A gaze contingent boundary paradigm (Rayner, 1975) was used; when readers' eye movements crossed an invisible boundary, a contextually plausible or implausible preview word would be replaced with a medium-frequency target word.
The results they found were very conclusive. Next to replicating the frequency effect on skipping, Veldre et al. also found a significant effect (of the same order as the frequency effect) of plausibility on skipping; readers had a higher skipping rate for plausible parafoveal words, rather than for implausible parafoveal words (Veldre et al., 2020). Thus, there is evidence for a plausibility effect on skipping.

3.2 Reader's language comprehension in relation to skipping rates

Language comprehension is the major focus of this thesis. Research has pointed out that a better language comprehension contributes to a higher skipping rate. Here I will discuss two relevant papers on this topic.

First, Eskenazi and Folk (2015) found that reading skill modulates skipping rates. Their research was based on findings by Brysbaert et al. (2005), Ashby et al. (2005) and Veldre and Andrews (2014). The main takeaway from these papers is that word difficulty is influential for skipping rates. Word difficulty is subjective, as it depends on how good the reader's language comprehension is. As low-skill readers take longer to identify words than high-skill readers (Ashby et al., 2005), and have bigger frequency effects than high-skill readers (Veldre & Andrews, 2014), it is suggested that low-skill readers have worse lexical representations. From this it is assumed that low-skill readers have a worse language comprehension.
Other findings include that high-skill readers benefit from phonological previews, given that it is a homophone preview (beech instead of beach) (Chace et al., 2005), and that high-skill readers have a larger perceptual span to extract information from (Veldre & Andrews, 2014). When posed with a gaze contingent moving-window paradigm (McConkie & Rayner, 1975), Veldre and Andrews found that high-skill readers' reading rate was quickest when reading a full line of text, where low-skill readers had the fastest reading with a window size of 11 characters. The conclusion was made that high-skill readers extract more information from

the parafovea and from multiple words during a single fixation (Veldre & Andrews, 2014, p. 721).

Eskenazi and Folk (2015) set out to find the extent of influence a reader's skill has on skipping. They wanted to see if the difficulty of a word in the fovea influenced skipping rates, and if a reader's skill modulated this. The subjects were asked to read sentences consisting of a three- or five letter target word, which was preceded by either a low- (difficult) or high-frequency (easy) word. This preview is called the foveal load, where a difficult word has a high foveal load and an easy word a low foveal load. Skipping rates of the target words were measured for both low- and high-skill readers. After the experiment, reader skill was assessed. The following examples were used in the experiment (Eskenazi & Folk, 2015):

High foveal load, <u>three letters</u>: The artist painted the *beige* <u>sky</u>, which clashed with the orange flowers.

Low foveal load, <u>three letters</u>: The artist painted the *black* <u>sky</u>, which clashed with the orange flowers.

High foveal load, <u>five letters</u>: The artist painted the *beige* <u>skirt</u> that the woman was wearing.

Low foveal load, <u>five letters</u>: The artist painted the *black* <u>skirt</u> that the woman was wearing.

The results are shown in table 2.

Table 2: skipping rates (%) for the multiple foveal load conditions.

	Low-skill reader		High-skill reader	
Foveal load condition	3 letter word	5 letter word	3 letter word	5 letter word
Low	61%	30%	60%	33%
High	48%	32%	57%	30%

It was found that three letter words (57%) were more likely to be skipped than five letter words (31%). For the three letter word condition, there was a statistically significant interaction between a reader's skill and the foveal load that was presented ($z = 2.71$). Low-skill readers had a 61% chance to skip a three letter word in the low foveal load condition, whilst only skipping 48% in the high foveal load condition. High-skill readers had no effect from the foveal load; the skipping rate was identical. In the high foveal load condition, three letter target words were skipped more often by high-skill readers than by low-skill readers (60% vs. 48%). For five letter words, there was no interaction between foveal load and reading skill. Their conclusion was that reading skill is important for word skipping, when moderated by word length and foveal load (Eskenazi & Folk, 2015). High-skill readers' greater parafoveal processing was found to be not only by the extended perceptual span, but also because of the phonological preview benefit proposed by Chace et al. (2005).

However, Slattery and Yates (2018) found contradictory results. Noting that not reading, but spelling skill influenced skipping rates. Their research was based on the findings that better readers have shorter gaze durations and longer saccades (Kuperman & Van Dyke, 2011), that readers with a high proficiency in language comprehension (i.e. high-skill spellers and high-skill readers) are better in extracting lexical information from upcoming words than people less proficient in language comprehension (Veldre & Andrews, 2015a) and the hypothesis that lexical processing can be constrained by parafoveal word length information (Veldre & Andrews, 2015b; Juhasz et al., 2008; White et al., 2005).
Slattery and Yates set out to see what contributed towards a better lexical representation. Spelling skill (zSpell) was assessed with the dictation and recognition tasks from Andrews and Hersch (2010) and reading ability was assessed by letting participants read a passage and grade their results with the Flesch-Kincaid grade level (Kincaid et al., 1975). The stimuli used were from Rayner et al. (2011). The experimental items contained two sentences with a target word in the second sentence, which was either highly or lowly predictable from the context. The target words were either of short, medium or long length (between 4-12 characters). Participants were instructed to read for comprehension and would read 54 experimental items, and 88 filler stimuli. Table 3 shows the skipping rates found in the experiment.

Table 3: the skipping rates for all the word length and predictability conditions

Word length	Predictability	Skipping rate (%)
Short	High	29.3
	Low	26.5
Medium	High	20.7
	Low	18.3
Long	High	10.7
	Low	8.5

These results were then analyzed with a generalized linear mixed model (McCullagh & Nelder, 1989) and a positive relation was found between zSpell and skipping likelihood (t value = 2.2). Reading ability only influenced gaze durations, and spelling ability only influenced skipping rates (Slattery & Yates, 2018, p.8), as opposed to the proposal from Eskenazi and Folk (2015) that reading skill influences word skipping rates. A possible explanation for this discrepancy is that better readers make longer saccades (Kuperman & Van Dyke, 2011) which can result in an accumulation of skipping rates due to accidental skips of target words. All in all, there seems to be enough evidence that language comprehension is a big modulator of word skipping in reading and should be accounted for in computational models on eye movements during reading.

3.2.1 Predictions related to skipping

According to Eskenazi, Folk (2015), Slattery and Yates' (2018) studies, EZ-Reader should predict that better readers have a higher skipping rate. Because low-skill readers will have more difficulty processing difficult words, low-frequency words are expected to be skipped more often by high-skill readers than low-skill readers. Additionally, the proportion of high-frequency words skipped versus low-frequency words skipped should be higher for low-skill readers as they rely more on frequency effects. Lastly, a more general prediction which is expected, is that skipping rates are around 20-30% (Rayner, 2009; Schotter et al., 2012).

Now we will turn to modeling the main findings using the EZ-Reader model. A description of EZ-Reader is given. Section 4.1 explains the skipping mechanism within the model. How the mathematical equations are implemented is discussed in section 4.2.

4 EZ-Reader description

EZ-Reader is based on two core assumptions (Sheridan & Reichle, 2015; Reichle et al., 2003). First, it is a serial attention shift (SAS) model. This means that the lexical processing (i.e. word identification) goes in a stricity serial manner. The attention shifts from one word to another. When word n (the word in the attention spotlight) is identified, the attention goes to word n+1. The second assumption is that saccades are programmed based on a preliminary stage of lexical processing called the familiarity check.

The model also makes smaller, more specific assumptions (Sheridan & Reichle, 2015; Reichle et al., 2003). It takes 50ms for visual information to reach the brain, referred to as attentional dwell time (Duncan et al., 1994; Treisman & Gelade, 1980). Lexical processing is done in two steps, a labile stage called L1 and a non-labile stage called L2, based on findings from Becker and Jürgens (1979), and can be denoted as responsible for orthographic and semantic processing respectively (Reingold & Rayner, 2006). During L1, the orthographic form of a word is identified. At this point there is no full lexical access. After L1 is completed, the oculomotor system begins programming a saccade to word n_{+1} . Saccadic programming is done in two stages: a labile stage (M1) and a non-labile stage (M2), where the time required to complete both stages is a random deviate from a gamma distribution with a mean of respectively 125 ms and 25 ms. M1 also has two sub-stages that are equally long. The first sub-stage prepares the oculomotor system for a saccade. In the second sub-stage, a location-to-distance transformation is done to determine the length of the saccade. Simultaneously, L2 is running, and full lexical access for word n is unlocked. Here the word's phonological and semantic forms are identified for additional linguistic processing. When L2 is complete, the attention then shifts to the next word, starting L1 for word n_{+1} . Implications for the decoupling of both lexical stages are that EZ-Reader can explain certain phenomena regarding when and where saccades are planned, e.g. the finding that parafoveally previewed words are fixated for shorter durations (Rayner, 1975). It is evident that lexical processing is the main factor driving the eyes through the text.

4.1 Skipping within EZ-Reader

Skipping is dependent on the oculomotor control within EZ-Reader. There are two important factors regarding skipping within EZ-Reader: word predictability (cloze probability) and word frequency. Saccade programming (where and when to move the eyes) is completed in two stages: M1 and M2. During the first sub-stage of M1, the eye movement system is made ready to begin programming a saccade. Afterwards, a saccade target (where the next fixation should land) is determined and the distance between launch site and fixation target is computed. M1 is subject to skipping, which has a few implications. When M1 is running in its first sub-stage, but is cancelled by a subsequent saccadic program, then the amount of preparation done so far is transferred to the second program, shortening the time required to complete it. But, if a second program is initiated during the location-to-distance transformation substage of M1, the processing done so far does not transfer over, because the distances of both saccades are different. If saccadic programming is in M2 and a new saccade program is initiated, then word n+1 is forcibly fixated for a short amount of time before word n+2 is fixated.

Now to see how this relates to skipping, consider this situation: word n is fixated and a program to fixate word n+1 is initiated. But during M1, L1 is finished for word n+1 and another program is initiated for moving the eyes to word n+2. This results in word n+1 being skipped as the eyes directly fixate on word n+2. According to Reichle et al. (2003), this allows EZ-Reader to successfully predict that words of high frequency are skipped more often, as this only happens when lexical processing for word n+1 is done quickly. However, when a second program is initiated during M2, the program to fixate word n+1 will first complete (thus word n+1 will be fixated) before the eyes move towards word n+2.

This relates to the skipping rates as during L1, only orthographic information is processed. It is found that orthographic information can be processed parafoveally (Chace et al., 2005; Juhazs et al., 2008; Schotter et al., 2012; Eskenazi & Folk, 2015) and from this incomplete information a guess can be made (as found by Brysbaert et al., 2005) on whether or not to skip the word. In EZ-Reader the orthographic information that is used by readers are word frequency and word predictability. Predictability is modeled with cloze probability: the probability that the target word completes a sentence based on the preceding context.Word frequency is how often the word occurs within a corpus of text. EZ-Reader predicts that when a word is highly frequent, or highly predictable from its preceding context, the reader will be able to determine this from parafoveally processed orthographic information, and the word will be skipped.

4.2 EZ-Reader implementation

This section gives an account of the implementation used in this thesis, for the purpose of running simulations. It is based on the description of Sheridan and Reichle (2015).

A valid model on eye reading should be able to account for basic properties of eye-movements during reading. These are the so-called benchmark data. There are five facts known about eye movements during reading (Rayner, 2009). The average fixation duration in reading is between 200 and 250 ms. Though, there is significant variability; some fixations can be under 100 ms or over 500 ms. A saccade is averaged to be between 7-9 letter spaces, yet it is also found that there is variability; better readers typically make longer saccades (Kuperman & Van Dyke, 2011). The skipping rate of readers is approximately 25-30% (Rayner, 2009; Schotter et al., 2012). Regressions are made about 10-15% of the time and measures on fixation duration are sensitive to specific properties of a word (Rayner, 2009). As such, the implementation explained below accommodates these central facts. The equations that are described output different important measures of the eye, from processing time to refixation probability.

The time it takes to complete L1 is given by equation 1:

1)
$$t(L_1) = 0 \qquad \textit{if } p < \textit{predictability}_n$$
$$t(L_1) = \alpha_1 - \alpha_2 ln(\textit{frequency}_n - \alpha_3 \textit{predictability}_n) \qquad \textit{if } p \geq \textit{predictability}_n$$

Here, the upper branch is true when a word is guessed from the preceding context, meaning L1 is completed in 0 ms. This happens with p, the cloze probability of word n. Cloze probability is normally assessed by letting (independent) participants try and fill in a blank space within a sentence, based on the context. The measure resulting from this is the mean proportion of occurrences that a word was predicted correctly from the preceding context (Taylor, 1953).

However, if a word is not predicted, the lower branch is true. The time required to finish L1 is assumed to be a linear function based on the frequency of word n within written text (data can be found in corpora, such as in Francis & Kucera, 1982; Davies, 2010) and its cloze probability, modulated by three free parameters: $\alpha_1 = 104$, $\alpha_2 = 3.4$ and $\alpha_3 = 39$ (Sheridan & Reichle, 2015). These free parameters were chosen so that the goodness-of-fit of the model was optimized (Reichle et al., 2003). The result is that L1 takes shorter (on average) to complete for predictable or frequent words.

The equation above is the mean time required to complete L1. Because there is a lot of variability in the time required to process a word, a second equation is introduced for L1. This is the actual time it takes to complete L1, which is a random deviate from a gamma distribution with a mean of 25 ms and a standard deviation of 0.18 (Reichle et al., 2003). The time required to complete L1 is given by equation 2:

2) $$t(L_1) \leftarrow t(L_1) \cdot \varepsilon \sum_{i=1}^{N} \left| fixation - letter_i \right| / N$$

This equation is the function of the mean eccentricity (which is the distance in character spaces) between the point of fixation, and each of the single letters of the word that are being processed. The free parameter $\varepsilon = 1.15$ is the amount of modulation on the slowing effect of visual acuity by eccentricity and i indexes the letters of word n. N is the total amount of letters in the word.

t(L2), the time required to complete L2, is given by equation 3:

3) $$t(L_2) = \Delta[\alpha_1 - \alpha_2 ln(frequency_n) - \alpha_3 \cdot predictability_n]$$

The time required to complete full lexical access is, just like for L1, a random deviate sampled from a gamma distribution. After L2, two things happen. First, attention shifts to word n+1, which takes on average 25ms (again, the real value is taken from a gamma distribution with mean 25ms). Second, postlexical integration starts for word n, denoted as l in the model. This is the minimum time required for the reader to deduct whether or not the word fits semantically and syntactically within a sentence. Because this is a background process with no observable effect on eye movements, this will not be discussed in detail.

EZ-Reader also assumes that a saccade is always intended to land in the middle of the target word. More specifically, just to the left of the center. This is called the optimal viewing position, and it provides the viewing position so that word identification is as quickly as possible (Clark & O'Regan 1999; O'Regan 1990; 1992b; O'Regan et al. 1984). Saccade length is calculated by equation 4:

4) $$saccade\ length = intended\ saccade\ length + systematic\ error + random\ error$$

The intended saccade length is the distance in character spaces between the launch site and the optimal viewing position of the word to be fixated. In EZ-Reader, the saccade length is also subject to systematic- and random error within the oculomotor system. Equation 5 denotes the systematic error:

5) $$systematic\ error = (\psi - intended\ saccade\ length) \cdot \{[\Omega_1 ln(fixation_{LS})]/\Omega_2\}$$

Systematic error is a function of the difference between the optimal saccade length $(\psi = 7)$ and the length between launch site and the optimal viewing position, and the time taken to fixate the launch site word $fixation_{LS}$. Saccades that are longer/shorter than 7 character spaces are subject to this error. The amount of over- and undershoot of the saccade is also modulated by the free parameters $\Omega_1 = 6$ and $\Omega_2 = 3$ that influence to which degree the fixation of the launch site matters.
Finally the random error is a random deviate, sampled from a Gaussian distribution with a mean of 0 character spaces. The standard deviation is given by equation 6:

6) $\sigma = \eta_1 + \eta_2 \cdot \textit{intended saccade length}$

Free parameters $\eta_1 = 0.5$ and $\eta_2 = 0.15$ are implemented to ensure that long saccades are more error prone than short saccades, as the variability of the random error increases with saccade length. The equations 4-6 taken together create a Gaussian-like distribution of fixation landing sites that mimic empirical results reported in literature (McConkie et al., 1988).

A final equation flows from the assumption that EZ-Reader makes about automatic refixations or rapid eye movements that are made after a fixation was made near the edge of a word. This is based on findings that fixations further from the optimal viewing position induces more difficult lexical processing (O'Regan & Lévy-Schoen, 1987). Thus the assumption made is that when a word is suboptimally fixated, there is a chance that a second corrective saccade is made on the word. The chance that this happens increases when the fixation location is further from the optimal viewing position (in character spaces) and is given by equation 7:

7) $p(\textit{refixation}) = \lambda \, |\textit{landing position} - \textit{saccade target}|$

Equation 7 also includes a free parameter, $\lambda = 0.16$ which modulates the strength of the saccadic error on the refixation probability.

Lastly, a few central assumptions of the model are discussed. A saccade requires 25ms to execute. Attentional dwell time (Duncan et al., 1994; Treisman & Gelade, 1980) is implemented and takes 50 ms after the eyes fixate a new location. Finally, the time that is available for parafoveal processing of word n+1 is modulated by the difficulty of word n. As the processing time for n increases, the time available for parafoveal processing decreases.

5 Simulation

This section is dedicated to the simulation and its results. 5.1 discusses the materials and procedure. How the parameters are chosen is explained in 5.2. Finally, the results are given in 5.3, together with a discussion of the results in section 6.

5.1 Materials and design

The GECO corpus (Cop et al., 2016) is used to run simulations on. This corpus includes monolingual and bilingual empirical eye tracking data of participants reading an entire novel. The bilinguals read the first half in their own language (Dutch), and the second half of the novel in English. Because of this, simulations are run on only the second half of the novel. As the bilinguals are reading in their second language, it is assumed that they have worse English lexical representations (i.e. worse language comprehension) than the monolinguals, thus the bilingual data is compared to the low-skill readers and the monolingual data to the high-skill readers.

Word frequency data is also gathered, from the BNC Corpus (Davies, 2004). Then words are split into two categories: low-frequency words and high-frequency words. Words that occur less than 100 in million are considered low-frequency, and more than 100 in million is high-frequency. This is done to measure skipping rates for low- and high-frequency words. In order to account for empirical results, EZ-Reader should predict that low-skill readers skip less low-frequency words as they are more reliant on word-frequency effects for skipping (Kuperman & Van Dyke, 2011; Veldre & Andrews, 2014) and are found to be less likely to skip words which are difficult (low-frequency words are often perceived as more difficult to process) (Eskenazi & Folk, 2015).

Simulations are run 900 times over the first 50 sentences (starting from the middle) of the corpus. The measures for both low- and high-skill readers are: Low-frequency word skipping rate (%), high-frequency word skipping rate (%) and Total skipping rate (%). The empirical data from the GECO corpus is also split into three skipping measures: a total skipping rate and a skipping rate for low- and high-frequency words. For consistency, the skipping rates are only taken over the same portion of text that the simulation is run over.
Simulations for low-skill and high-skill readers are done independently of each other, as the implementation of different reading skills depends on changing certain parameters. In the following section this will be discussed.

5.2 Setting parameters

To investigate whether differences in skipping rates for high-skill spellers and low-skill spellers can be implemented within EZ-Reader, the duration of L_1 is modified. For simplicity, better language comprehenders are described as high-skill readers. This section also touches on the word parameters' values.

5.2.1 Model parameters

t(L_1) is modified by changing the free parameters α_1 , α_2 and α_3 . Alpha 1 denotes the maximum time that can be spent on L_1 . Alpha 2 controls to which degree a word's frequency influences L_1 's processing time and the latter controls to which extent predictability influences t(L_1). Brysbaert et al. (2005) discussed that readers make a general guess based on orthographic information obtained from the parafovea, on whether or not to skip a word. Additionally they noted that word difficulty influences skipping rates. Other findings include that low-skill readers take longer to identify words, and have bigger frequency effects than high-skill readers (Ashby et al., 2005; Veldre & Andrews, 2014). According to this information better readers should have a smaller t(L_1).

As better readers should take less time to complete L_1 , Alpha 1 is smaller for high-skill readers than it is for low-skill readers. Alpha 2 is higher for low-skill readers, because they rely more on word-frequency effects during reading. Based on the assumption that high-skill readers are better at predicting words from a preceding context, alpha 3 is higher for high-skill readers than for low-skill readers. This is because high-skill readers know more words, thus can make a better guess for which words fit the current context.

Not only will the parameters be based on literature, but also on how the parameters interplay with each other. To this extent I will show how each parameter influences skipping rates individually. Every parameter will be changed to a higher value once, whilst the other two remain at their base value. These modulations are quite considerable to show the effect more clearly. Then, the skipping rates are given together with the parameter modulation. The base-value of the parameters are taken from Reichle et al. (2003): $\alpha_1 = 104$, $\alpha_2 = 3.4$, $\alpha_3 = 39$. Table 4 gives the skipping rates per modulated parameter.

Table 4: how each single parameter influences skipping rates. The first row gives the base values as intended by Reichle et al (2003) with $\alpha_1 = 104$, $\alpha_2 = 3.4$, $\alpha_3 = 39$. The other rows show the skipping rates when one parameter is modulated.

Parameter value	Low-frequency skipping rate (%)	High-frequency skipping rate (%)	Total skipping rate (%)
Base values	24.63	43.12	31.34
$\alpha_1 = 130$	24.79	30.71	23.91
$\alpha_2 = 4.4$	27.64	59.21	40.67
$\alpha_3 = 60$	24.92	44.35	32.09

What can be seen is that alpha 1 primarily modulates the high-frequency skipping rate. Alpha 2 has influence on all skipping rates, but primarily the high-frequency skipping rate. Alpha 3 is a very small modulator of skipping rates (words like “the” will have quite a high predictability effect, yet most words have cloze probabilities of < 0.01, so alpha 3 will have little to no effect on them) and also primarily influences the high-frequency skipping rate. From this, and an iterative best-fitting process, the parameters have been chosen. Table 5 shows the final parameter values.

Table 5: an overview of the parameters for low- and high-skill readers used in the simulation. The parameters were iteratively changed to give the best possible fit to empirical data.

	Low-skill reader	High-skill reader
α_1	150	100
α_2	3.4	3
α_3	20	44

5.2.2 Word parameters

The main workhorse behind skipping in the E-Z Reader model is the duration of L_1. Next to the 3 free parameters within the equation of L_1, there are two other factors that influence its duration: word frequency and predictability. Word frequency is the number of occurrences that a word has within the text corpus. This information has been obtained through usage of the BNC Corpus (Davies, 2004), which is a corpus containing 100 million English words from a wide variety of sources.

Predictability is based on the conditional chance that word x finishes a trigram. The ngram frequencies are also obtained via the BNC Corpus (Davies, 2004). The probability of word x finishing a trigram (a,b,x) is the frequency of (a,b,x) divided by the frequency of bigram (a,b). Every first two words within a sentence have an assigned predictability value of 0, as a trigram can not be made until the third word in a sentence.

5.3 Results

First, the empirical results are discussed. As is consistent with literature (Ashby et al. 2005; Veldre & Andrews, 2014) low-skill readers are less likely to skip low-frequency words. Only 7,88 % of the low-frequency words that were passed in the text were skipped. On the other hand, high-skill readers skipped 20,61% of the low-frequency words. The total skipping rate for low-skill readers is 21,73% and high-skill readers note a skipping rate of 31,54%. This is consistent with literature, as Rayner et al. (2012) note that skipping rates should be between 25-30%. The complete results can be found in table 5:

Table 6: skipping rates for mono- and bi-linguals measured during the reading of GECO corpus.

	Low-skill readers	High-skill readers
Low-freq skipping rate (%)	7.88	20.61
High-freq skipping rate (%)	36.87	46.54
Total skipping rate (%)	21.73	31.54

The simulation results are quite contradictory with the results noted above. EZ-Reader predicts similar total skipping rates for low-skill (24,7%) and high-skill (31,02%) readers. Yet the low- and high-frequency skipping measure predictions are anomalous. The most notable is that low-skill readers are predicted to skip 23,43% of the low-frequency words. An overview of the EZ-Reader predictions can be found in table 6:

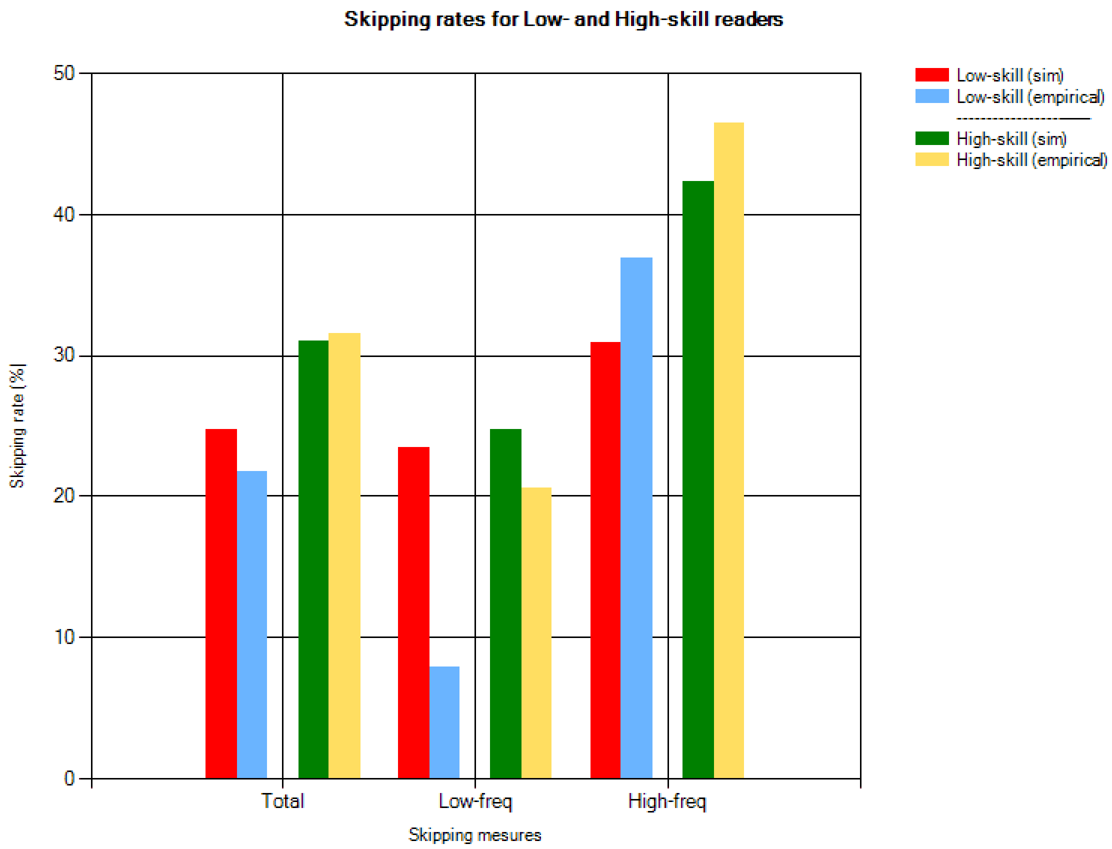
Table 7: skipping rates predicted by EZ-Reader. Simulations were run over 50 sentences (428 words) and iterated 900 times.

	Low-skill readers	High-skill readers
Low-freq skipping rate (%)	23.43	24.73

High-freq skipping rate (%)	30.90	42.38
Total skipping rate (%)	24.70	31.02

The following graph is shown for easy comparison of the measures:

Graph 1: barplot of the 4 skipping measures



In conclusion, EZ-Reader can manage to replicate the total skipping rates for different skill levels in reading. Yet it falters when taking into account the skipping rates for low- and high-frequency words. As was found by Eskenazi and Folk (2015), a low-skill reader will have more complications processing a difficult word, resulting in lower skipping rates for low-frequency words. This is not the case for the simulation results, where empirical- and simulation data have a gap of 15%. Moreover, the low-frequency skipping rates are very similar for the low-and high-skill reader simulations while this should be the measure where differences between reader skills should be highest (as can be seen in the empirical data). Evidently, EZ-Reader has not made the correct predictions in order to account for reader skill modulation on skipping rates.

6 Discussion

The results from the simulation show us that EZ-Reader can not account for the modulation of skipping rates by a reader's language comprehension. At least, not by only changing the duration of L_1 .

Successful predictions from EZ-Reader are that high-skill readers have a higher skipping rate and that the proportion of high-frequency words skipped versus low-frequency words skipped is larger for low-skill readers. Yet the other predictions are questionable at best.

Interestingly, the results posed in table 6 are inconsistent with findings from Mcgowan and Reichle (2018, p 8.). They note a simulated total skipping rate of 26% for low-skill (older) readers and 24% for high-skill (young) readers. Here, alpha 1 was also modulated accordingly for low- and high-skill readers. The discrepancy in results could be due to different goals. Mcgowan and Reichle also had measures for regressions and fixation duration in order to replicate a slower reading rate and increased fixation count for older readers. As such, the parameter fitting process did not take into account skipping rates.

EZ-Reader is able to predict correct total skipping rates for low- and high-skill readers. The total skipping rates for low- and high-skill readers should be around the range of 20-30% (Schotter et al., 2012). These findings are also concurrent with findings by Reichle et al. (2013), noting that changing parameter alpha 1 could replicate basic patterns of eye-movements for adult (skilled) and children (less-skilled) readers.

However, when word-frequency is taken into account, EZ-Reader falters. The predictions made about the frequency specific skipping measures are off by at least 4%. Most notably, the difference between the predicted and actual skipping rates of low-frequency words by low-skill readers is off by 15,55%. A possible explanation is that EZ-Reader's skip mechanic is too simple; as it is based on only the processing time for L_1 . Theories found in literature pose multiple explanations for skipping (Drieghe et al., 2004; Drieghe et al., 2019; Eskenazi & Folk, 2015; Brysbaert et al., 2005; Slattery & Yates, 2018), yet none assume skipping to be solely dependent upon lexical processing time. For future versions of EZ-Reader it may be beneficial to look into other factors than lexical processing as influencers for eye-movement control.

Additionally, the interplay of the parameters a_1 , a_2 and a_3 suggests that there is no regard for word-frequency specific skipping rates within EZ-Reader. This makes parameter-fitting extremely difficult and provides an explanation for the incorrect predictions made by EZ-Reader. All the parameters influence at least the high-frequency skipping rate, yet none influence only the low-frequency skipping rate. Moreover, EZ-Reader hugely overestimates the skipping probability of low-frequency words (the lowest reported is 23.43%). An implication of this, is that when the skipping rate is too high for low-frequency words, it can not be remedied with the parameters as this will also influence total, and high-frequency skipping rates. Thus, fitting the parameters to replicate total skipping rate data will result in incorrect predictions for both the low- and high-frequency skipping measures and vice versa.

That being said, a model is supposed to account for a wide range of data. From this perspective, it is perhaps not the best idea to change the skipping mechanism as this could interfere with other mechanisms within the model; skipping, like a lot of other measures are based (at least partly) on L_1 and changing this can have big implications for the model's flexibility. Right now EZ-Reader is able to account for a lot of empirical results concerning eye-movements during reading (i.e. Reichle et al., 2013; Mancheva et al., 2015). And due to its simplicity EZ-Reader motivated a lot of new research, providing a simple theoretical framework for eye-movement control during reading (Reichle & Sheridan, 2015).

These results are relevant for AI as they contribute to a better understanding of human eye movements during reading. Skipping decisions are shown to be different for readers of different skill levels. Additionally, EZ-Reader is shown to have flaws for its skipping mechanism. It is evident that in order to model skipping correctly the mechanism should be changed. From an AI perspective this is interesting because now it is shown that a model can not correctly predict skipping by just modulating the duration of L_1 (the familiarity check). This knowledge can be used to improve human eye movement models, which attributes to better human behavior modeling.

Finally, this simulation has shown that only changing t(L_1) is not sufficient to explain the differences in skipping behavior of low- and high-skill readers. These results suggest that lexical factors alone are not enough to explain skipping rates for low- and high-skill readers. Through this, I hope this thesis can contribute towards a better understanding of how reading skill is a modulator on a reader's skipping decisions.

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Project on github

The simulation can also be found on Github with the following link: https://github.com/Tvanp/ezreaderthesis. Look at the Readme file before running.

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