The role of the oculomotor control in eye movements during reading

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Abstract

Most reading theories assume that readers aim at word centers for optimal information processing. During reading, saccade targeting turns out to be imprecise: Saccades' initial landing positions often miss the word centers and have high variance, with an additional systematic error that is modulated by the distance from the launch site to the center of the target word. The performance of the oculomotor system, as reflected in the statistics of within-word landing positions, turns out to be very robust and mostly affected by the spatial information during reading. Hence, it is assumed that the saccade generation is highly automated.

The main goal of this thesis is to explore the performance of the oculomotor system under various reading conditions where orthographic information and the reading direction were manipulated. Additionally, the challenges in understanding the eye movement data to represent the oculomotor process during reading are addressed.

Two experimental studies and one simulation study were conducted for this thesis, which resulted in the following main findings:

(i) Reading texts with orthographic manipulations leads to specific changes in the eye movement patterns, both in temporal and spatial measures. The findings indicate that the oculomotor control of eye movements during reading is dependent on reading conditions (Chapter 2 & 3).

(ii) Saccades' accuracy and precision can be simultaneously modulated under reversed reading condition, supporting the assumption that the random and systematic oculomotor errors are not independent. By assuming that readers increase the precision of sensory observation while maintaining the learned prior knowledge when reading direction was reversed, a process-oriented Bayesian model for saccade targeting can account for the simultaneous reduction of oculomotor errors (Chapter 2).

(iii) Plausible parameter values serving as proxies for the intended within-word landing positions can be estimated by using the maximum a posteriori estimator from Bayesian inference. Using the mean value of all observations as proxies is insufficient for studies focusing on the launch-site effect because the method exhibits the strongest bias when estimating the size of the effect. Mislocated fixations remain a challenge for the currently known estimation methods, especially when the systematic oculomotor error is large (Chapter 4).

The results reported in this thesis highlight the role of the oculomotor system, together with underlying cognitive processes, in eye movements during reading. The modulation of oculomotor control can be captured through a precise analysis of landing positions.

Zusammenfassung

Zahlreiche Theorien des Lesens gehen davon aus, dass Sakkaden beim Lesen auf die Wortmitte abzielen, um eine optimale Informationsverarbeitung zu erreichen. Die Landepositionen von Sakkaden verfehlen oft die Wortmitte und weisen eine hohe Varianz auf, mit einem zusätzlichen systematischen Fehler, der durch die Entfernung zwischen der Sakkadenstartposition und der Position der Wortmitte moduliert wird. Das Verhalten der Okulomotorik, wie es sich in der Statistik der Sakkadenlandepositionen widerspiegelt, erweist sich als sehr robust und wird hauptsächlich von räumlichen Informationen beeinflusst. Daher wird angenommen, dass der Sakkadengenerierungsprozess automatisiert ist.

Das Hauptziel dieser Dissertation ist es, das Verhalten des okulomotorischen Systems unter verschiedenen Lesebedingungen zu untersuchen. Hierzu wurden orthographische Informationen und die Leserichtung manipuliert. Blickbewegungsdaten repräsentieren den okulomotorischen Prozess beim Lesen. Die Herausforderungen beim Verständnis dieser Daten wurden thematisiert.

Insgesamt wurden zwei experimentelle Studien und eine Simulationsstudie durchgeführt, die zu folgenden Hauptergebnissen führen:

(i) Die Blickbewegungsmuster beim Lesen von Texten mit manipulierter Orthographie veränderten sich spezifisch zur jeweiligen Bedingung, sowohl in zeitlichen als auch räumlichen Kennwerten der Blickbewegungsdaten. Dies legt nahe, dass sich die okulomotorische Kontrolle beim Lesen an die Manipulation anpasst (Kapitel 2 & 3).

(ii) Sowohl Genauigkeit, als auch Präzision von Sakkaden lassen sich durch die veränderte Leserichtung verbessern. Das Ergebnis zeigt, dass systematische und zufällige Fehler des okulomotorischen Systems nicht unabhängig sind. Das Bayes'sche Model zur Sakkadenplanung kann die empirischen Ergebnisse approximieren und zeitgleich die verbesserte Sakkadenausrichtung erklären. In der Rechts-nach-Links Lesebedingung verbessert sich die Präzision von sensorischen Informationen, während das a priori erlernte Vorwissen unverändert bleibt (Kapitel 2).

(iii) Plausible Parameterwerte, die als Annäherung für intendierte Landepositionen dienen, können durch Verwendung des maximalen a posteriori Schätzers aus der Bayes'schen Inferenz geschätzt werden. Die einfache Mittelwertsmethode weist die stärkste Verzerrung bei der Schätzung der Effektstärke des Launch-Site-Effekts auf. Daher ist sie nicht ausreichend, um den Effekt zu beschreiben. Falsch verortete Fixationen bleiben eine Herausforderung für die derzeit bekannten Schätzmethoden, insbesondere wenn der systematische okulomotorische Fehler groß ist (Kapitel 4).

Die in dieser Arbeit berichteten Ergebnisse unterstreichen die Rolle des okulomotorischen Systems - zusammen mit den zugrundeliegenden kognitiven Prozessen - bei der Blicksteuerung beim Lesen. Die Modulation der okulomotorischen Steuerung kann durch die genauen Analysen der Sakkadenlandepositionen erfasst werden.

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Chapter 1

Introduction

Reading, the ability to extract visual information from written text, is one of the most important skills needed in modern society. The use of eye movements measures has improved our understanding of the processes involved in reading because they allow specific assumptions to be tested through experimental studies (see Rayner, 1998, 2009, for a review). Since visual acuity is limited to the central visual field (the fovea), the eyes compensate this limitation by generating short and rapid movements (saccades) to shift the fovea to the regions of interest where visual information can be encoded optimally during fixations (Findlay & Gilchrist, 2003). Readers typically move their eyes forward about 6-7 letter spaces in the text to attend to upcoming words and remain relatively still on a word for about 200-250 ms for information extraction. Research using eye movement measures has demonstrated that reading is a complex skill that involves visual processing under the perceptual span, attention allocation during fixations, word processing and oculomotor processes for planning and generating saccades (Rayner et al., 2012). In general, eye movement control during reading requires the coordination of the cognitive system in selecting the saccadic target word and the oculomotor system in generating saccades to bring the fovea to the target word for high-acuity information processing.

By using eye movement measures, research in reading has been trying to understand where and when the eyes move during reading (Rayner, 1998). Typical eye movement measures in reading are fixation durations, fixation probabilities, and oculomotor measures such as saccade lengths or fixation positions within words. While the temporal aspects of eye movement measures such as fixation durations (e.g., first fixation duration, gaze duration and total viewing time) are associated with the information processing load or cognitive processes, the spatial eye movement measures such as saccade lengths and within-word landing positions characterize the performance of oculomotor system during reading (Rayner et al., 2012). Additionally, the interaction among those qualitative measures has resulted in effects that can be experimentally tested (see Kliegl et al., 2004, for an example). Therefore, investigating the interplay between cognitive and oculomotor systems is crucial to understand the underlying processes involved in eye movement control during reading.

The most important experimental finding in investigating the processes involved in reading is the effect of word frequency on fixation durations, i.e., the average fixation duration for words seen less frequently is longer than for words seen more frequently, which represents the information processing load (Rayner, 1998). There has been a long-standing controversy about whether word processing is done in a serial or parallel manner. However, recent findings have shown that during reading, several words can be processed at the same time. When the eyes are fixating on the target word N, the neighboring word $N + 1$ (Schotter et al., 2012) and $N + 2$ (Kliegl et al., 2007; Risse & Kliegl, 2014; Radach et al., 2013) are also processed. In addition to corpus analysis (Kliegl et al., 2007, 2006), experimental studies applied gaze-contingent presentation of text. For instance, in the boundary paradigm (Rayner, 1975; Rayner et al., 1980), where letters or the complete word changed after the participants moved their eyes across the invisible boundary between two words, parafoveal word processing can be inferred more precisely.

The oculomotor control of eye movement was characterized by the statistics of landing position within words, whose distributions approximate the Gaussian distribution function with relative high variance (Rayner, 1979). One of the most important findings on the oculomotor system during reading is the *launch-site effect* (McConkie et al., 1988), a systematic shift of the mean landing positions towards the target word center as a function of launch-site distance. In a study on isolated words, it was reported that word recognition time is the fastest when fixations land near the word center(the *optimal viewing position (OVP) effect*; O'Regan & Jacobs, 1992). The OVP effect, although to a lesser extent, was also observed during reading normal sentences (Vitu et al., 2001).

Eventually, recent findings indicating an interaction between the oculomotor effect and the fixation duration effect during reading were reported. Fixation durations were the longest when the eyes landed on the word center and reduced as the eyes landed further away from the word center (the *inverted optimal viewing position (IOVP) effect*; Vitu et al., 2001). Nuthmann et al. (2005) explained these findings by proposing that saccades landing on word edges were mostly mislocated and were corrected immediately for optimal processing, hence the observed short fixation duration. Additionally, they proposed that mislocated fixations were one of the sources for the high variability of the distributions of within-word landing positions during reading.

Results from experimental studies have led to the development of computational reading models that serve as a tool to understand the underlying processes involved in eye movement control during reading. Most prominent computational reading models, e.g., E-Z Reader (Reichle et al., 2003); SWIFT (Seelig et al., 2020; Engbert et al., 2005); Glenmore (Reilly & Radach, 2006); SERIF (McDonald et al., 2005); or OB1 (Snell et al., 2018), assume that linguistic variables (e.g., word frequency) are accountable for the decision of "when" to move the eyes, while visuomotor aspects (e.g., computation of target distances) are important for the decision ”where” to move the eyes next. The "where" decision consists of the process of selecting the saccadic target word and the execution of saccades to shift the fovea to the target location (Rayner, 1998). With the assumption that cognitive and oculomotor systems are independent, those models are able to approximate human reading behavior and replicate experimental effects reported in reading experiments. Furthermore, the models incorporate the random and systematic errors of saccades based on the mathematical formulation and the numerical values reported by McConkie et al. (1988) to represent the oculomotor system in eye movements during reading. With more evidence suggesting that eye movements during reading are the result of the interplay between both cognitive and oculomotor systems, computational models can be optimized by integrating process-oriented assumptions and formulations to represent the oculomotor system. To isolate the underlying process affecting the observation, one should manipulate factors associated with a single process while controlling the remaining factors (Schad et al., 2010). The main focus of this thesis is to acquire new information that characterizes the oculomotor performance during reading while considering different processes underlying eye movement control during reading. By systematically investigating the effect of manipulation of spatial information of text (e.g., through inversion of letter positions or reversing the reading direction) on the statistics of within-word landing positions and the launch-site effect, new insights on the role of the oculomotor system in eye movements during reading can be obtained.

Finding experimental effects in within-word landing positions is not trivial. Among the complex eye movement patterns observed during reading, one should decide which measures are informative to describe the observed eye movement behavior during reading and what method to use for the data analysis. Numerous studies reported the general performance of oculomotor control during reading such as the average saccade amplitudes, the average launch-site distances and the composite distribution of within-word fixation positions across all word lengths tested (e.g., White & Liversedge, 2004). Several studies analyzed the initial fixations landing on words (e.g., Rayner, 1979; Hyönä, 1995; Farid & Grainger, 1996) and others extended further to explore the relationship between the mean landing sites and the launch-site distances (the launch-site effect) to quantify the performance of the oculomotor system during reading (e.g., McConkie et al., 1988; Vonk et al., 2000). Other studies reported the launch-site effect for different saccade types (e.g., Krügel & Engbert, 2010; Krügel et al., 2012).

The following sections describe our current understanding of the statistics of within-word landing positions, representing the oculomotor control during reading.

1.1 Within-word landing positions

Prevalent theories of reading and eye movement agree that readers aim their saccades at word centers where visual information can be extracted optimally, *the optimal viewing* *position (OVP)*, referring to the location within a word where refixation probability is at the lowest (O'Regan & Jacobs, 1992; Clark & O'Regan, 1999; Vitu et al., 1990). However, the eyes do not always land on the intended target location. The within-word fixation positions approximate a Gaussian distribution, truncated on word edges, with the mode located halfway between word beginning and word centers and contained surprisingly high variance. The mode of the within-word fixation positions is termed *preferred viewing location (PVL)*, which is variable depending on word length (Rayner, 1979). Similar observations were reported in reading studies on different languages such as German (Kliegl et al., 2004; Radach & McConkie, 1998), French (Vitu et al., 1990), Hebrew (Deutsch & Rayner, 1999) and Arabic (Jordan et al., 2014). Even when the linguistic information was absent, the statistic of within-word landing positions still follow the normal distribution. For instance, during mindless reading, where participants read meaningless letter strings such as "zzzz" or "xxxx" (Nuthmann et al., 2007; Rayner & Fischer, 1996; Vitu et al., 1995). The findings have led to the assumption that the oculomotor process involved in reading is not directly linked to linguistic features of words and the saccade generation during reading is highly automated.

Orthographic familiarity and regularity influence landing positions (Hyönä, 1995; White & Liversedge, 2004, 2006b). Hyönä (1995) reported that when readers processed words with highly irregular clusters, their fixations landed closer toward the beginning of words, particularly to the white space preceding the fixated words. Unlike its well-documented effect on fixation durations, word frequency has only a small effect on within-word landing positions. Compared to low-frequency words, saccades launched to fixate on high-frequency words landed mostly towards the second half of the words (Nuthmann, 2006). The effect of word predictability on where the eyes land during reading is not clear. In the study reported by Lavigne et al. (2000), a shift of initial fixation location towards the end of high predictable words was observed, but only when those target words also possessed high frequency at the same time and only for saccades launched near the target words. On the other hand, Rayner et al. (2001) reported that word predictability had little effect on the initial landing position on the target words and suggested that the small effect observed was partly due to the eyes attempting to skip the high predictable target words but failing to do so. Moreover, they reported that the mean landing position was further into the word as word length increased, suggesting that low-level processing is primarily responsible for landing position effects in reading (see Vainio et al., 2009, for similar findings).

As previously mentioned, the launch-site effect (McConkie et al., 1988) serves as the most important effect of the oculomotor control during reading. In their influential study, McConkie et al. (1988) reported when the mean landing positions and launch-site distances were measured relative to the center of target words, the effect of word length diminished. As a result, this relationship between the launch-site distances and the shifts of mean landing positions from word centers can be described as a linear function, the *landing* *position function* (Radach & McConkie, 1998), which can be formulated as

$$\Delta\mu = \lambda \cdot (L_0 - L). \tag{1.1}$$

where $\Delta\mu$ refers to the shift of the mean landing position from the word center and the parameter L represents the launch-site distance to the saccadic target word. The parameter L_0 represents the optimal saccade length, that is, fixations launched from this distance land on the word center, on average. The parameter λ represents the strength of the launch-site effects, i.e., how far the means of fixation landing positions shift away from the target word center with decreasing/increasing launch-site distance. McConkie et al. (1988) reported the estimated value of $\lambda \approx 0.5$, that is, for every unit increment of launch-site distance, the discrepancy between mean landing position and word center increases with the magnitude of half a character.

1.2 The range-error model

To explain their findings on the launch-site effect, McConkie et al. (1988) proposed the range-error model by introducing two independent systematic and random error components. The first error component is the systematic variation of mean landing sites towards the word centers as a function of launch-site distance observed in reading can be understood as a manifestation of a basic principle of controlled muscle movement, realized in the form of the saccadic range error (Poulton, 1981). Assuming that word centers serve as the saccadic functional target, the mean of the landing site distribution is accurate when the launch-site distance is between 6 and 7 character spaces to the left of that target, represented by the parameter L_0 in the Eq. (1.1). Saccades launched from distances further or closer than the optimal launch site L_0 resulted in undershoots and overshoots respectively. The strength of this systematic error component is presented by the parameter λ in Eq. (1.1).

Moreover, McConkie et al. (1988) provided the basis on how to interpret the estimated value of the slope parameter λ by presenting two extreme data patterns that could have been observed in eye movements during reading. In the first scenario, it would have been possible to find that the eyes always land on the center of the words, with a portion of random error in achieving that target. In this case, no relation between launch site and mean landing site (i.e., $\lambda = 0$) would have been obtained, indicating a completely center-based saccade targeting. In the second scenario, it would have been possible to find that the eyes are sent to a particular distance by generating saccades with constant average lengths all the time, i.e., there is no functional target location within words. In this case, there would have been a perfect relationship between the change in launch-site distance and the shift of the mean landing site from the word center (i.e., $\lambda = 1$), with word centers having no influence on saccade targeting. However, the estimated value of $\lambda \approx 0.5$, which is between the two possible extreme values, was reported in the study, suggesting that there exists a word-based targeting process, but at the same time, saccades generated are biased towards constant average lengths.

The second type of the oculomotor error is the random variation of landing sites around the mean, which approximates a normal distribution and increases with the distance to the target location. This source of error is referred to as perceptual-oculomotor variability (Poulton, 1981). The size of this error is indicated by the standard deviations of the landing site distributions. Although the variability is represented as random, it may include systematic variability due to individual differences in the functional target within words and the effects of stimulus characteristics, e.g., what type of texts being presented, or characteristics of the prior sequence of eye movements (McConkie et al., 1988). Furthermore, Nuthmann et al. (2005) identified at least four different types of mislocated fixations to account for the relatively high variability of within-word landing positions observed during reading.

In the range-error model, both systematic and random error components are completely independent. Changes in one error component do not necessarily affect the other error component. Although the range-error model was able to describe the oculomotor mechanism during reading in general, it did not predict that the variability observed can be modulated. Based on the range-error model, it is unclear why saccades during reading tend to be generated with average constant amplitudes as the model did not explain the underlying processes of saccade planning. For example, Krügel & Engbert (2010) reported that the estimated size of the launch-site effect for word-to-word forward saccades was smaller than those for skipping saccades, which could not be explained by the range-error model. Furthermore, the range-error model did not make any predictions in cases where reading conditions deviated from the normal reading condition.

1.3 The Bayesian model of saccade planning

Recently, the Bayesian model of saccade planning was introduced to describe the underlying processes in the oculomotor control, as reflected in the statistics of within-word landing positions. This section summarizes the theoretical framework for the Bayesian model of saccade planning (Engbert & Krügel, 2010; Krügel & Engbert, 2014). Since reading represents a highly constrained visual environment, it is assumed that readers apply Bayes' rule to reduce the uncertainty associated with the sensory estimate of the target location by integrating the sensory likelihood with internal prior knowledge about the distribution of saccade targets during reading. According to this theory, the observed systematic and random errors of fixation positions within words during reading are the consequence of saccade planning based on noisy and incomplete knowledge of the saccade target position.

Given that reading represents a highly constrained visual environment (i.e., the sensory systems have no direct access to parameters in the environment), an optimal approach for sensory estimation is to maximize the conditional probability $\pi(x|x_o)$. In the case of reading, it is the probability of a target at position x given a sensory estimate at position x_o. Following the general formulation of Bayes rule in sensory-motor integration (Körding, 2007; Körding & Wolpert, 2004, 2006), the posterior probability $\pi(x|x_o)$ is the product of the likelihood $q(x_o|x)$, the conditional probability of sensory estimate (or observation) at position x_o given a target position at x, and a sensation-independent, prior probability $p(x)$ of saccade target positions, which can be formulated in the form of

$$\pi(x|x_o) \propto q(x_o|x)p(x) \ . \tag{1.2}$$

To compute the explicit forms of the distributions of landing positions according to Bayesian decision theory, all probability densities are assumed to follow the Gaussian distribution function. The prior distribution, $p(x) \sim \mathcal{N}(x; \mu_t; \sigma_t^2)$, is centered at the average distance of μ_t of target locations from the launch site with the variance σ_t^2. The likelihood, $q(x_o|x) \sim \mathcal{N}(x_o; x, \sigma_o^2)$, is modeled as an unbiased distribution with the peak positioned at the center of the intended word of the incoming saccade and with variance σ_o^2 expressing the degree of sensory uncertainty. The resulting posterior distribution is another Gaussian distribution function, $\pi(x|x_o) \sim \mathcal{N}(x; \mu_p; \sigma_p^2)$, where

$$\mu_p = \frac{\sigma_o^2 \mu_t + \sigma_t^2 x_o}{\sigma_o^2 + \sigma_t^2} \tag{1.3}$$

and

$$\sigma_p^2 = \frac{\sigma_o^2 \sigma_t^2}{\sigma_o^2 + \sigma_t^2} \ , \tag{1.4}$$

which serves as a natural explanation of the launch-site effect because the peak μ_p is located between the maxima of prior and likelihood distributions. The posterior estimates tend to overestimate the distance of the center of close target words and systematically underestimate the distant target locations. Furthermore, the random saccadic errors (σ_p^2) correlate positively with the uncertainty of the sensory likelihood (σ_o^2) and/or the variance of the prior distribution (σ_t^2).

The systematic shift of the mean of the estimated posterior distribution, μ_p, from the observation x_o can be calculated as

$$\Delta\mu_p = \mu_p - x_o = \frac{\sigma_o^2}{\sigma_o^2 + \sigma_t^2}(\mu_t - x_o) \ , \tag{1.5}$$

where the coefficient $\sigma_o^2/(\sigma_o^2 + \sigma_t^2)$ is similar to the parameter λ in Eq. (1.1), representing the magnitude of the launch-site effect.

Unlike the range-error model, the systematic and random error components of the within-word fixation distributions are inherently linked together and their estimated values depend on the amount of observational error (σ_o^2) and the uncertainty of prior knowledge (σ_t^2) about the distances between the current fixation location and the saccadic target location. The formulations of the mean and standard deviation in Eq. (1.3 & 1.4) as the representation of the distribution of within-word fixation positions make psychologically plausible predictions for the two extreme cases of complete observational uncertainty and insignificant observational error. When the observation does not contain useful information about the target location (e.g., $\sigma_o^2 \to \infty$), the resulting posterior distribution equals the prior distribution. On the other hand, when the observation is perfectly localized (e.g., $\sigma_o^2 \to 0$), the resulting posterior distribution is not influenced by the prior knowledge about the target location.

The Bayesian model for saccade planning proposes that the strength of the systematic error component depends on the relative uncertainty of the prior distribution and the sensory likelihood. When sensory observations contain useful information about the target location (reflected in the decreased likelihood variance), it will reduce the launch-site effect of systematic error components (i.e., decreased estimated value of slope parameter λ). However, a reduced variance of prior distribution will result in an increased effect of the launch-site distance on the systematic error component of within-word landing positions. The estimated value of $\lambda \approx 0.5$ typically reported in experimental data (McConkie et al., 1988; Nuthmann et al., 2005) implies that the observational uncertainty of target location in reading is approximately the same as the standard deviation of the prior distribution.

1.4 Methods for estimating within-word landing positions

Since the observed saccades during reading are realized saccades, there is no direct way to know whether readers intend to land their saccades on certain target words. A common practice is to assume certain parameter values, e.g., the mean and standard deviation, as the proxies for the intended within-word landing position. However, estimating the parameters for the word-based distribution of fixation positions is not trivial because the observed fixations on a particular word N also contain fixations originating from saccades intending to land on the neighboring words (Kliegl et al., 2006; Nuthmann et al., 2005). The mislocated fixations, i.e., fixations from saccades that land on unintended target words, increase the variance of the distribution of fixation landing sites, providing challenges in estimating parameters to represent the proxies of the intended landing locations within words (Engbert & Nuthmann, 2008; McConkie et al., 1988). Furthermore, the distribution of fixation landing site is often truncated at the word edges. Since our interpretation of the oculomotor performance during reading depends strongly on the estimation results, the method used should be able to deliver plausible results despite the challenges associated with the within-word landing positions.

There are three methods currently used to estimate the parameters for the proxies of the within-word landing positions. Some studies use the arithmetic means and standard deviations of fixation position data as the proxies for the intended landing position (e.g., Ablinger & Radach, 2015; White & Liversedge, 2006b). Other studies fitted the fixation data to the Gaussian distribution function individually (e.g., Nuthmann et al., 2005; Engbert & Nuthmann, 2008) or by assuming that all distributions are mutually informed (e.g., Chandra et al., 2019).

1.5 The present studies

Chapters 2-4 of this thesis reported the three studies investigating the effect of different reading conditions on the oculomotor system in eye movement control during reading. All studies were conducted to improve our understanding of parameters that affect the oculomotor performance during reading and to simulate situations where those parameters could have changed. Chapters 2 and 3 reported data from reading experiments. In Chapter 2, orthographical information of texts were manipulated in four conditions: word-wise mirroring (mW), letter-wise mirroring (mL), inversion (iW), and letter position scrambling (sL). In Chapter 3, the reading direction was reversed while typical letter positions in words were kept intact. The studies report eye movement recordings from 69 participants reading 600 lines of text from the German version of the novel ”The Adventure of the Empty House” (Doyle, 2009). Furthermore, Chapter 4 reported simulation data of more than 35 statistical participants reading the first 150 lines of text from the same novel where the parameters that regulate the oculomotor process during reading were systematically changed to test the plausibility of different estimation methods in reconstructing the known value and the implication of different parameter values on the data generated by different reading models.

1.5.1 Modulation of oculomotor control during reading of mirrored and inverted text

The study reported in Chapter 2 was designed to explore the interplay between the cognitive and oculomotor processes during reading by manipulating the spatial layout of texts (word-wise and letter-wise mirrored-reversed text as well as inverted and scrambled text) while maintaining the linguistic information of texts. Specifically, it was interesting to know how far the cognitive processes in target word selection can overwrite the highly automated oculomotor mechanism. In this study, various eye-movement measures were investigated. In line with the findings reported in previous studies, reading performance was slowed down, reflected in the observed longer mean fixation times but shorter average saccade lengths, during reading of texts with orthorgraphic manipulation compared to the reading of normal texts. These measures were typically associated with the overall processing difficulty during reading.

It is unclear whether the oculomotor targeting processes during reading can adapt to the orthographic changes of texts. The performance of the oculomotor system during reading is reflected in the statistics of within-word landing positions and specifically characterized in the launch-site effect. Precise analysis of landing positions was carried out and substantial changes in the launch-site effect were reported. Specifically, a reduced launch-site effect was observed in the experimental conditions where letter positions were reversed and read against overall reading direction. An increased launch-site effect was observed in the other experimental conditions. These results indicated that the oculomotor system is adaptive to the unusual reading conditions.

Furthermore, the distributions of within-word landing positions observed in the experimental conditions are more precise than those observed in the normal reading condition. However, since each manipulation has specific characteristics associated with processing difficulties, the improved precision of landing positions can be the result of the prolonged fixation times due to word processing or purely improved oculomotor control.

1.5.2 Experimental test of Bayesian saccade targeting under reversed reading direction

As a follow-up study, Chapter 3 reported the study where only the reading direction was manipulated. Specifically, the reading direction was reversed (texts were read from right to left) while the writing direction of texts was kept intact (written normally from left to right). The motivation of this experimental study was twofold. First, it is to minimize the effect of word processing difficulties on the oculomotor performance. Second, to experimentally test the Bayesian model of saccade planning since it makes explicit assumptions about the origin and the amount of random and systematic errors within the oculomotor system during reading.

In general, reversing reading direction resulted in longer fixation duration measures but no substantial change in saccade lengths. Furthermore, when texts were read against the typical reading direction, the estimated launch-site effect was reduced. This replicated the finding of the study reported in Chapter 2 where texts were written against the overall reading direction. This is particularly remarkable as it has been shown that the launch-site effect during reading is very robust (McConkie et al., 1988; Nuthmann, 2006; Reilly & O'Regan, 1998). Moreover, it was shown that the systematic and random error components of within-word landing position distributions could be simultaneously reduced by reversing reading direction.

The Bayesian model of saccade planning was able to account for the observed effects on saccades' random and systematic error components during reading under the normal left-to-right reading condition and the reversed reading condition. The model simulation results suggested that improvement in the precision of sensory likelihood was able to explain the reduction of both random and systematic error components associated with the oculomotor control during reading.

1.5.3 On estimating within-word fixation positions: Comparison of three estimation methods

Despite the assumption that the systematic launch-site effect during reading is very robust, the studies reported in previous chapters showed that the launch-site effect can be modulated by manipulating the spatial layout of texts or by reversing the reading direction. Those findings changed our way of understanding the launch-site effect on within-word landing positions. Moreover, our interpretation of the performance of the oculomotor control of eye movements during reading depends on how the proxies for the intended landing positions were estimated. There are at least three commonly used methods to estimate the parameters characterizing the distributions of within-word landing positions: (1) the mean value of all observations, (2) the peak of truncated Gaussian distribution, and (3) the maximum a posteriori estimator from Bayesian inference. The study reported in Chapter 4 was designed to test the plausibility of those three methods in estimating the parameter μ and σ representing the mean and standard deviation of the individual distribution of within-word landing positions. Since the launch-site effect plays an important role in quantifying the performance of the oculomotor system during reading, the three methods were also tested for their plausibility in estimating the slope parameter λ of the landing-position function.

To test the plausibility of the three estimation methods, fixation data were generated using two different reading simulations by systematically changing the input value the parameter λ from 0 to 1 with a step value of 0.1, resulting in 22 datasets with known values of the slope λ. For each dataset, data with different sample sizes were sampled for fixations landing on 3- to 8-letter words and launched from 1 to 6 characters away, resulting in 36 word-based distributions of fixation landing positions. The methods were applied to estimate the parameter μ and σ for each word-based distributions and the resulting slope parameter λ. The mean estimation bias from each method served as an indicator for each method. As a result, the Bayesian approach is most reliable, even for small sample sizes (e.g., N = 20), in reconstructing the parameters. While the simple arithmetic method works well in estimating individual word-based distributions, it shows the strongest systematic bias when estimating the λ parameter of the landing-position function that characterizes the oculomotor process during reading.

Furthermore, the study also simulated the scenarios where the systematic error components of oculomotor performance varied, for instance, the scenario where the target selection process during reading was absent (e.g., $\lambda = 1$). In this scenario, all of the tested methods could not effectively reconstruct the known parameters, especially the slope parameter λ that characterize the oculomotor performance during reading. While the Simple arithmetic mean method showed systematic underestimations, the Gaussian and Bayesian fitting methods overestimated the parameter λ, due to the added noise from mislocated fixations (e.g., failed skipping saccades or refixations).

Chapter 2

Modulation of oculomotor control during reading of mirrored and inverted text

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Running head: Reading mirrored texts

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Abstract

The interplay between cognitive and oculomotor processes during reading can be explored when the spatial layout of text deviates from the typical display. In this study, we investigate various eye-movement measures during the reading of text with experimentally manipulated layout (word-wise and letter-wise mirrored-reversed text as well as inverted and scrambled text). While typical findings (e.g., longer mean fixation times, shorter mean saccade lengths) in reading manipulated texts compared to normal texts were reported in earlier work, little is known about changes of oculomotor targeting observed in within-word landing positions under the above text layouts. Here we carry out precise analyses of landing positions and find substantial changes in the so-called launch-site effect in addition to the expected overall slow-down of reading performance. Specifically, during reading of our manipulated text conditions with reversed letter order (against overall reading direction), we find a reduced launch-site effect, while in all other manipulated text conditions, we observe an increased launch-site effect. Our results indicate that the oculomotor system is highly adaptive when confronted with unusual reading conditions.

2.1 Introduction

Visual acuity is greatest at the center of the visual field (the *fovea*) and declines sharply on the periphery, which limits the information extraction process of visual input from the environment. To compensate for this limitation, the eyes generate short and rapid movements, *saccades*, to shift the fovea to the regions of interests for high-acuity information processing (Findlay & Gilchrist, 2003). During reading, the eyes move forward about 6 to 7 character spaces, on average, during saccades and fixate on a word for about 200 to 250 ms to support word processing. The control of (saccadic) eye movements requires the coordination of several fundamental cognitive subsystems such as word recognition, attention (Engbert et al., 2005), and oculomotor control (Reichle et al., 1999). While the cognitive system is responsible for selecting which word to be fixated next, it is the oculomotor system that is responsible for shifting the fovea to the regions of interests for high-acuity information processing (Findlay & Gilchrist, 2003). Thus, our reading ability depends on the oculomotor performance, whose properties are reflected most clearly in the statistics of within-word fixations, typically the eyes' landing position on words after saccades.

Unlike the well-documented effects of cognitive modulation on temporal aspects (e.g., fixation duration) of eye movement measures (e.g., Kliegl et al., 2004; Rayner, 2009), small effects of cognitive modulation on spatial aspects (e.g., within-word landing position) of eye movement measures were reported (Albrengues et al., 2019). For example, orthographic familiarity and regularity influence landing positions (Hyönä, 1995; White & Liversedge, 2004, 2006a,b). Furthermore, corpus analyses showed a significant effect of word frequency on mean fixation position: Saccades landed further into the (3- to 6-letter) target word when it was a high-frequency word as compared to a low-frequency word (Nuthmann, 2006). A shift of initial fixation location toward the end of high predictable words were reported, but only when the words were seen more frequently and for saccades launched near the word beginning (Lavigne et al., 2000). On the other hand, Rayner and colleagues (2001) reported that word predictability had little influence on initial landing position on words and suggested that landing position effects in reading were primarily modulated by low-level processing. Finally, data from z-string scanning (where all letters were replaced by the letter "z" or "Z") indicated that within-word landing position distributions are very stable and do not critically depend on meaningful content (Nuthmann, Engbert, & Kliegl 2007; see also Luke & Henderson, 2013). Moreover, most effects of higher-level processing on the mean fixation position are small (< 0.5 character spaces).

Interestingly, the within-word landing positions were reported to influence the "higher-level" processes. In several studies, it was reported that (isolated) word recognition time was at the minimum when the eyes land at the center of the word compared to when the eyes land on the word's periphery, termed the *optimal viewing position (OVP)* (O'Regan

& Lévy-Schoen, 1987; O'Regan et al., 1984). A similar but weaker effect was observed on refixation probability in reading: readers were less likely to refixate the words if fixation land near the word center (Vitu et al., 2001). Oppositely, the average single fixation duration is the greatest when the eyes land at word center, termed the *inverted optimal viewing position* by Vitu et al. (2001). To explain the effect, Nuthmann and colleagues (2005) argued that fixations observed on the word edges were typically originated from saccades that were not intended to land on that particular word (mislocated fixations), hence the short fixation duration observed.

The observed evidence reported in reading research is the result of the integration of cognitive processes in word selection and oculomotor processes in shifting the eyes to the area of interests. To isolate the underlying process affected the observation, one should manipulate factors associated with one process while controlling the remaining factors. Kolers and Perkins (1975) used geometric rotations, reflections and other transformations of text as the physical variation to study the recognizability of the texts and how far the practice in reading one type of transformation could be applied on the recognition of other transformations. They found that the tested transformations varied in difficulty and transferability. Likewise, Kowler and Anton (1987) applied similar types of transformation to test the effects on global saccade lengths and fixation durations. By observing eye movement patterns of two participants, they reported that the directional pattern of saccades had relatively modest effects on reading speed under the instruction to read accurately. They argued that the reading time was affected by the longer time needed to generate short saccades observed in reading difficult texts. In a separate test, they found a negative relationship between saccade length and saccade latency: short saccades (less than 30') have longer latency than long saccades. Additionally, as a response to the Internet myth, Rayner et al. (2006) tested different types of word transposition (internal, beginning, and end of word) on reading time and reported that although participants were able to read the text, reading time was slower for some transposition types, especially when the word beginning was transposed. Hence they concluded the importance of word beginning (see White et al., 2008, for similar conclusions). Following the above approach of presenting texts in unfamiliar representation, we designed a study with four different experimental conditions and a control condition to systematically investigate the possible modulations of oculomotor processes in response to variations of the spatial layout of texts. Furthermore, the current study employs various eye movement measures to describe the oculomotor performances during reading.

In this study, letter positions and word representations were experimentally manipulated in the following ways: We used texts composed of mirror-inverted letters (mL), mirror-inverted words (mW), inverted words (iW), where regular letters are printed in reverse order, and scrambled letters (sL) (see Figure 2.1a for examples). In mirrored-words (mW) and mirrored-letter (mL) conditions, either the complete word or the constituting letters were mirror-inverted with respect to the vertical axis. In contrast, no mirroring was involved in the construction of inverted-word (iW) and scrambled-word (sL) text conditions. In inverted words (iW) condition, letter representation was normal, but the position was inverted in the iW condition to mimic the letter position in the mW condition. In scrambled letters (sL) condition, the positions of the first and the last letter of a word were maintained, while the letter positions in between were randomized (i.e., there was no change in words with length less than 4 letters). The condition mL, mW, and iW are equivalent to the condition NNV, NRV and NRN applied in the study reported by Kowler and Anton (1987). The condition sL is equivalent to the internal transposition manipulation in the study reported by Rayner et al. (2006).

The following sections describe the robust finding on within-word landing position distribution during reading and the proposed models to explain the observed phenomena. Furthermore, we will discuss current reading models and their predictions, particularly on saccade generation and "where" the eyes land, according to the manipulations applied in this study.

2.1.1 Within-word landing positions

Regarding "where" the eyes land during reading, a robust finding is that within-word landing position approximately follows a Gaussian density function, with a pronounced peak, typically located halfway between word beginning and word center, but with a surprisingly large variance (Rayner, 1979; McConkie et al., 1988; O'Regan, 1990). The landmark study by McConkie et al. (1988) identified two independent oculomotor error components in reading, which we will denote as the *range-error model* throughout this article: (i) The *random placement error* is assumed to reflect perceptual-oculomotor inaccuracy in the execution of saccades, which can be approximated by a Gaussian distribution. (ii) The *saccadic range error* represents a systematic, launch-site contingent shift of mean landing positions and is typically explained as a general response bias of the human motor system (Poulton, 1981).

Specifically, McConkie and colleagues (McConkie et al., 1988) found that during reading, the within-word landing positions varied systematically with the launch-site distance, i.e., the distance between fixation location (before the saccade) and the beginning of the target word. The stable observation in reading is that each letter increment of the saccade launch-site generates a shift of mean landing-site with a magnitude of about half a character space to the left, the *launch-site effect*, which is independent of the target word length. If the distances between launch-sites and landing sites are measured relative to word centers, then the within-word mean landing position can be described by a linear landing-position function (see also Radach & McConkie, 1998) of the form

$$\Delta_\mu = \lambda \cdot (L_0 - L), \tag{2.1}$$

where Δ_μ denotes the average shift of the within-word mean landing position from the word center and L is the distance between launch site and the center of the target word. While a negative value of Δ_μ indicates that the within-word mean landing position shifts to the left of the word center, a positive value indicates a rightward shift. The parameter L_0 represents the center-based launch-site distance, where saccades land precisely on the word center, on average. The strength of the launch-site effect is represented by the slope parameter λ. An estimated slope of $\lambda \approx 0.5$ was observed in readers of English (McConkie et al., 1988) and German (Nuthmann et al., 2005) texts.

While the range-error model was generally a successful first description of the eye-movement data, certain effects reported in experimental studies could not be explained within this model. Recent studies reported that the presence of additional stimuli could influence the saccadic landing positions (Coëffé & O'Regan, 1987; Deuble et al., 1984; Findlay, 1982; Vitu, 1991, 2008; Vitu et al., 2006). Krügel & Engbert (2010) demonstrated that saccade type (i.e., word skipping) could influence the saccade landing positions during reading (see also Krügel et al., 2012; Radach, 1996). The range-error model did not provide explicit assumptions about the sources and the amount of oculomotor error observed during reading.

It is important to note, however, that the range-error model is purely descriptive since it does not include more fundamental computational principles for oculomotor control. Furthermore, the slope parameter of λ represents a quantification of the strength of the launch-site effect, without direct inferences on what processes underlying the observed phenomenon. As a consequence, it is not surprising that integrating new experimental evidence in the range-error model is difficult. In the next section, we discuss a process-oriented Bayesian model for saccade planning that was developed over the last 10 years.

2.1.2 A Bayesian model of oculomotor control in reading

The framework of Bayesian decision theory has been proposed as a principled approach to the optimal control of human behavior in the context of integration of sensorimotor and cognitive processes (Körding, 2007; Körding & Wolpert, 2004, 2006). Since saccadic eye movements require both sensorimotor (i.e., moving the eyes to foveate words) and cognitive processes, Engbert and Krügel (2010) proposed that eye movement control during reading could be explained using Bayesian estimation. According to Bayes rule (e.g., Wolpert & Ghahramani, 2005), the optimal estimate of a target position x, given a sensory observation at x_0, can be calculated as the conditional probability (posterior)

$$\pi(x|x_0) \sim q(x_0|x)p(x), \tag{2.2}$$

where $p(x)$ is the previously learned prior distribution of the target, independent of current sensory input, and the conditional probability $q(x_0|x)$ is the sensory likelihood of the observation at position x_0 given a target at x. The relation in Eq. (3.2) determines the dependence of the posterior probability from x. The missing constant of proportionality can be obtained by normalization.

Krügel & Engbert (2010) proposed that the dependence of landing positions within a word on the saccadic launch site is a special case of the Bayesian principles, Eq. (3.2), for saccade planning in reading. In a mathematical model, the likelihood $q(x_0|x)$ was modeled as an unbiased, normally distributed probability density centered at the intended target word and with variance σ_0^2, which represents the degree of sensory uncertainty. Assuming that the prior distribution is also normally distributed, the product of the two Gaussian density functions results in another normal density function, the posterior probability density $\pi(x|x_0)$. The posterior probability provides a natural explanation of the launch-site effect, since the position of its maximum falls between the maximum of the prior distribution and the maximum of the sensory likelihood. As a result, the posterior reproduces the systematic tendencies of saccades (i) to overshoot the center of close target words and (ii) to undershoot the center of distant target words (Engbert & Krügel, 2010). The shift of the mean of the posterior μ_P from the observation x_0 can be calculated as

$$\Delta_{Bayes} = \mu_P - x_0 = \frac{\sigma_0^2}{\sigma_0^2 + \sigma_T^2}(\mu_T - x_0), \tag{2.3}$$

where σ_T^2 is the variance of the prior probability of center-based launch-site distances. Comparing the equation for the launch-site effect, Eq. (3.1), with the predicted effect in the Bayesian theory, Eq. (2.3), thus assuming $\Delta_\mu \equiv \Delta_{Bayes}$, we obtain

$$\lambda = \frac{\sigma_0^2}{\sigma_0^2 + \sigma_T^2} \ . \tag{2.4}$$

Recently, Krügel & Engbert (2014) introduced an advanced model, which includes an explicit model for the computation of the word center from sensory estimates of word boundaries. Therefore, the Bayesian model can provide a robust theoretical framework to explain "where" the eyes move during reading. One advantage to model within-word landing position distribution using an explicit Bayesian model is the interpretability of the results. The slope parameter λ estimated from the Bayesian model represents the weighting of optimal behavior during reading: maintaining constant saccade length while targeting word center. For an extreme case where $\lambda \to 0$, it can be interpreted that the optimal oculomotor control in reading puts more weight on the precision in landing on target precision, hence minimizing range error. On the other hand, the value of $\lambda \to 1$ means that the optimal reading behavior relies on maintaining constant saccade length, reducing the importance of target location. With the typical empirical value of $\lambda \approx 0.5$, it can be interpreted that the sensory variance of the target location is approximately the same as the variance of the prior distribution, i.e., $\sigma_0^2 \approx \sigma_T^2$, in optimal reading behavior.

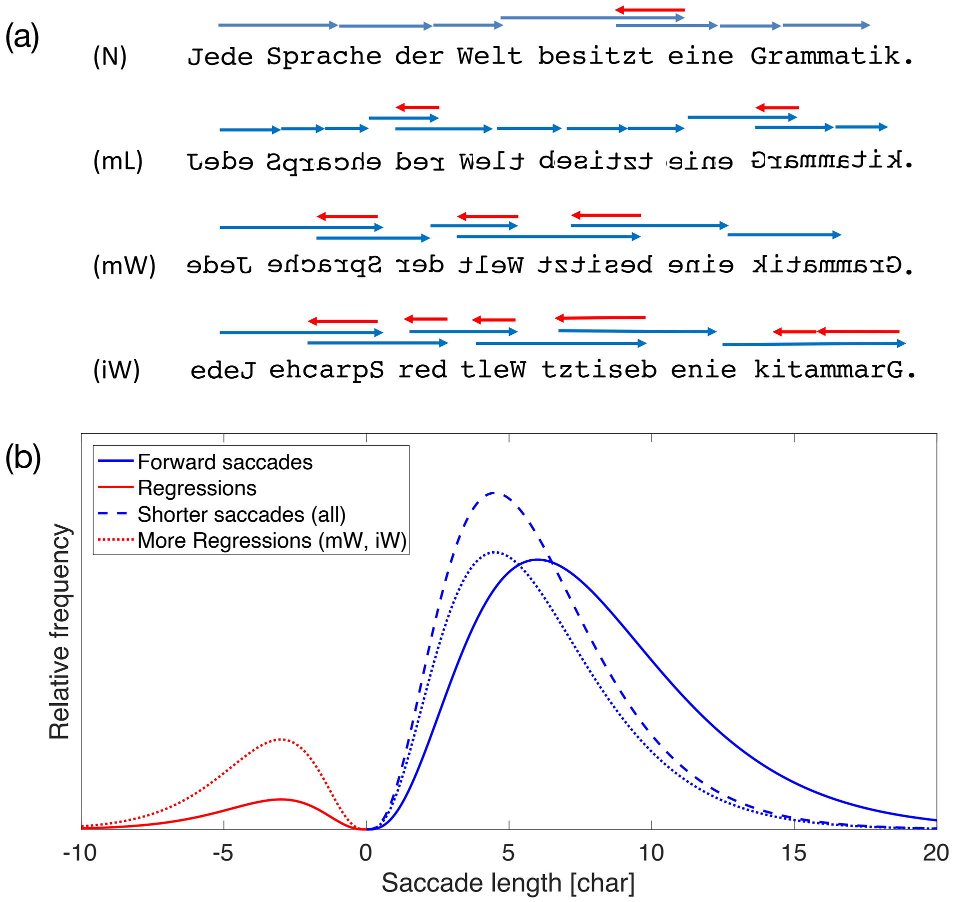


Figure 2.1: Experimental sentence stimuli and hypotheses on saccade lengths. **(a)** In the control condition, normal German text (N) is presented; for reading mirrored letters (mL) and scrambled words (sL), we expect shorter saccade lengths, on average. For mirrored words (mW) and inverted words (iW), word beginnings and word ends are exchanged, so that we expect longer mean saccade lengths and more regressions due to more frequent re-readings of the same string. **(b)** The distribution of saccade lengths (solid lines) and the expected changes due to the experimental manipulations.

2.1.3 Hypothesis and predictions from various reading models

Reading models were typically developed to improve our understanding of the complex processes underlying reading processes. Even though that eye movement control during reading requires both cognition and oculomotor systems, as mentioned above, empirical studies found that cognition had small effects on within-word landing positions. Interestingly, adding additional visual cue (Nuthmann, 2006) or changing sentence presentation, i.e., texts are read from top to bottom (Johnson & Starr, 2018), did not notably change the landing position distributions on words. Consequently, most mathematical models of saccade generation during reading assume that oculomotor control is dissociated from cognitive processes. Cognitive-based reading models such as E-Z Reader (Reichle et al., 1998, 2006, 2009) or SWIFT (Engbert et al., 2002, 2005; Schad & Engbert, 2012) assume that cognitive processes related to language processing are responsible for eye movements without distinguished effects on oculomotor within-word targeting process. Moreover, most cognitive models based their implementation of saccadic errors on the range-error model (McConkie et al., 1988) with relatively fixed values. Since the manipulation types tested in this study maintain the spatial information such as word length, cognitive-based models will not predict substantial changes in within-word landing positions since they assume that oculomotor processes are mainly affected by "low level" information. However, since orthographic manipulations will increase processing loads, hence affecting saccade generating time, these models will generate more refixation saccades but less skipping saccades.

Most relevant to the current study is Mr.Chips (Legge et al., 1997, 2002), an ideal-observer model that combine visual, lexical, and oculomotor information optimally to read simple texts in the minimum number of saccades. The model operates according to an entropy-minimization principle, generating saccades that minimize uncertainty about the current word or saccades that move the visual span furthest to the right. Note that for Mr.Chips, a word is said to be fixated if the central slot of the visual span (a linear array of character slots with each slot can be either high or low resolution) falls on one of the letters of the word and this central slot does not have preferred status. Mr. Chips' skipping rate and global landing position distribution were similar to human data. Mean saccade length decreases as the lexicon size increases. Furthermore, it generated fewer refixations and reduced launch-site effect ($\lambda = 0.21$) in reading normal text. Given that word identification played a key role for lexical processing in the model, we speculate that if the words were written from right to left (e.g., in mW and iW conditions), Mr. Chips should generate more saccades that land on the second half of a word to capture more information about word identity, assuming that the first half of the word was identified beforehand and that letter mirroring and inversion do not affect its lexical access process.

Our hypothesis for eye-movement measures on reading unfamiliar typography is derived from the predicted increase in perceptual difficulty and additional oculomotor demand. Longer fixation durations and shorter saccade amplitudes can be expected for more difficult texts in all four conditions. Increased perceptual difficulty should also result in less skipping cases, but more refixations; both of these predictions are compatible with a reduced average saccade length (see Figure 2.1b).

On the level of within-word landing positions, our hypotheses are more specific for the different experimental conditions. Since information on letter positions did not change (mL) or did not deviate systematically from normal reading (sL), reading words with mirror-inverted letters (mL) or with scrambled letters (sL) will produce within-word landing positions similar to normal reading. However, due to inversion of letter positions in reading mirrored-words (mW) and inverted words (iW), we expect readers to shift their eyes further to the right of the word string in the initial saccade and to generate a regressive refixation after that initial saccade (see Figure 2.1a).

Our study employs a learning paradigm, where participants are required to train reading text in one of the four experimental conditions. The motivation for the learning paradigm is to check the stability of the resulting eye-movement patterns and to exclude the possibility that the results are a short-lived effect due to the first exposure to an unfamiliar layout.

In general, we expect that the training will lead to improved performance on the level of global reading measures (average fixation times and mean saccade lengths). Since the scrambled letters (sL) condition represents the least systematic variation of the text layout, we expect that the learning effects are smaller than in the other three experimental conditions. On the level of within-word landing positions, we expect that stable shift of the initial landing positions toward the end of the word strings will be established during learning in the conditions with mirrored words (mW) and inverted words (iW), since the word beginnings are at the end of the manipulated strings in these two conditions. For the other two conditions (mL, sL), we expect that within-word landing positions are very similar to normal reading after training.

2.2 Methods

2.2.1 Participants

A group of 37 participants (27 females, 10 males), aged between 16 and 39 years, received a total of EUR 70 for taking part in four 45-minute lab sessions and six 30-minute training sessions. They were all naive with respect to the purpose of the experiment. Participants reported normal or corrected-to-normal vision and declared their informed consent. The experiment conformed to the Declaration of Helsinki. Informed consent was obtained for experimentation by all participants. According to the standards of Deutsche Forschungsgemeinschaft (German Research Foundation) and German Society for Psychological Research, ethics committee approval was not required for this study.

2.2.2 Apparatus, Material & Procedure

Participants were assigned to four different groups based on four types of text manipulation, namely mirrored-word text (mW), mirrored-letter text (mL), inverted-word text (iW), and scrambled-word text (sL). Each participant did a total of four lab sessions and six training sessions at home via a web-based interface.

For lab sessions, participants read an excerpt from the German version of the novel "The Adventure of the Empty House" (Doyle, 2009). They were seated at a viewing distance of 70cm in front of a 19-inch Mitsubishi Diamond Pro 2070 Monitor (screen

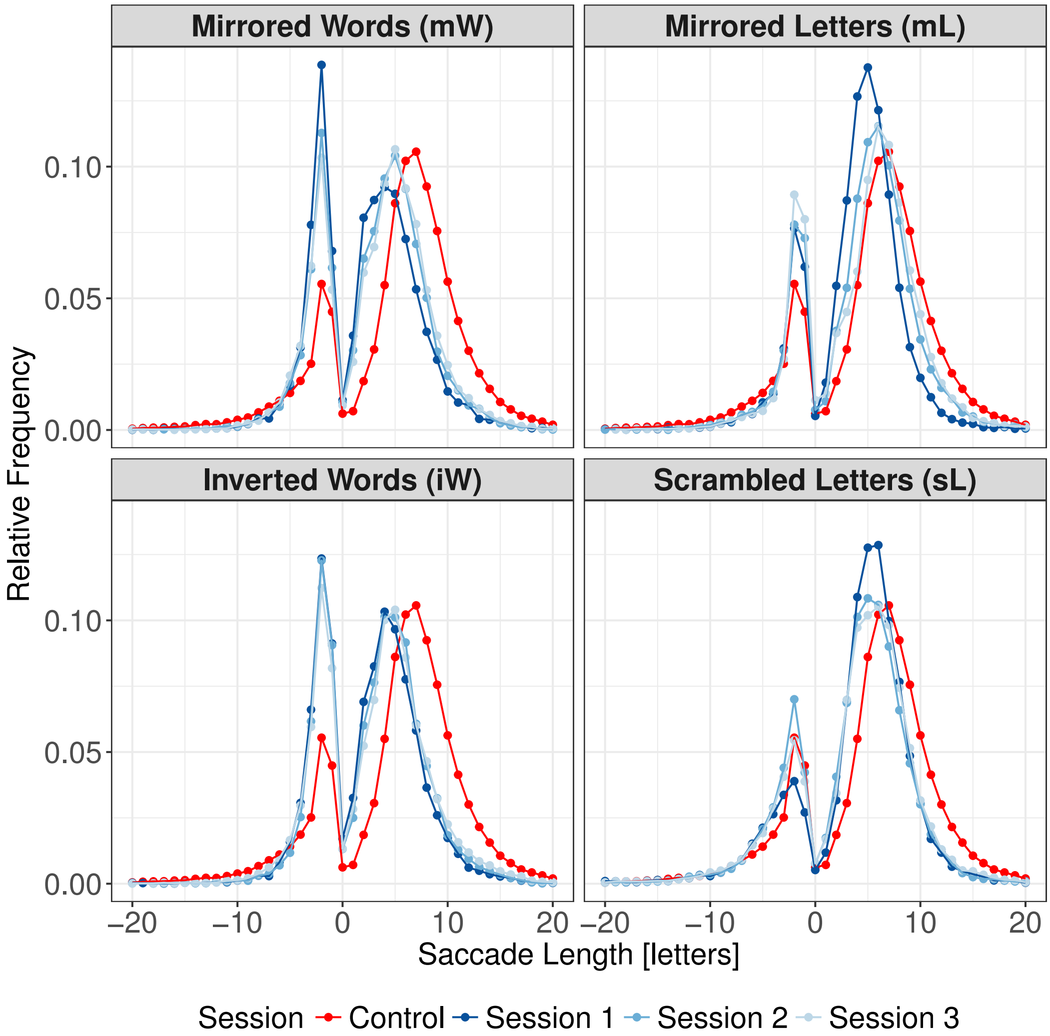


Figure 2.2: Distribution of saccade amplitudes across all sessions. Saccades observed in the control condition (normal reading) are marked with red color. Dark blue lines represent data from the first session of reading manipulated text. Data from the last two training sessions are marked with lighter blue hues.

resolution 1,280×1,024 pixels, refresh rate 100 Hz) with the head supported by a chin rest. The stimuli (Courier font, size 18, black) were presented on the vertical centerline of the computer display with a gray background color. Eye movements from both eyes were recorded using an EyeLink 1000 System (SR Research, Osgoode/Ontario, Canada) with a sampling rate of 1000 Hz and spatial resolution better than 0.01°. At the end of the session, participants had to answer three questions related to the text they have just read. A maximum of 600 lines of text were presented across all lab sessions.

For training sessions, participants read an excerpt from the novel "Small World" (Suter, 1997) by visiting a website created for the experiment[1]. After logging in, participants could read the manipulated text, which was presented as a line of max. 85 characters at the center of the screen, without time limit. When finished, they could go to the next line by clicking the right arrow or return to the previous page by clicking the left arrow. One training session should last at least 30 minutes. After logging out, participants received

[1]Using ShinyApps by RStudio accessible via `http://www.shinyapps.io`

three questions via E-mail, which should be answered as soon as possible. No limit of the number of lines presented in training sessions was enforced.

The complete procedures of the experiment went as follows: During the first lab session, participants read a normal text (a total of 150 lines, maximum 85 characters on each line). After a two-hour break, participants read manipulated text in the second session, which lasted up to 45 minutes or when 150 lines were read. At home, participants were required to read manipulated text for two 30-minute sessions on the website before the third lab session. At the third lab session, participants continue reading a manipulated text from where they left off at the previous session. Participants should conduct four 30-minute training sessions before taking part in the last lab session.

2.2.3 Data Preparation

Data containing blinks were discarded from the analysis. Saccades and fixations were detected using a velocity-based algorithm developed by Engbert et al. (2003). As a result, a total of $380,292$ fixations were detected. From this set of data, we excluded fixations based on the following criteria (i) fixations on the first and last words of a sentence as well as the first and the last of participant's fixation sequence; (ii) fixations with duration less than 20 ms or longer than 1000 ms, fixations landing outside the text rectangle, and saccades shorter than one character space (12 pixels) or longer than 25 character spaces were removed from the analysis. Trials containing fixation duration longer than 2000 ms and less than three fixation points after filtering were excluded from the analysis. The remaining $236,937$ fixations are the valid fixations (see Table A1 in Supplementary Information).

2.3 Results

Reading text with manipulated layout due to mirrored-reversed and inverted letter arrangement produced changes in behavioral measures on a global level (e.g., mean fixation duration, average saccade length) and on the oculomotor level (i.e., within-word fixation locations/ saccadic landing positions). While the primary goal of our study was to investigate the possible modulations of oculomotor processes in response to variations of the spatial layout of texts, we start with the presentation of results on global summary statistics to evaluate the overall effects on reading performance as characterized by eye-movement measures.

2.3.1 Global summary statistics

This section highlights the significant results for each manipulation across training session in comparison with normal reading. If not otherwise mentioned, results refer to comparisons between the first experimental session (in one of the four conditions mW, iW, mL, or sL) and the control condition (normal reading).

First of all, global summary statistics from the reading normal texts are replicated. In the control condition, most of the first-pass fixations move forward to the next neighboring words (forward saccades, 41 %) or skip (skipping saccades, 26 %). About 22 % of the fixations move within a word (refixation saccades) and 12 % of them move backward (regression saccades). On average, readers move their eyes 7.82 character spaces forward, 4.23 character spaces backward and fixated on words for 245 ms during reading normal text. Compared to the control condition, the percentage of forward saccades in the experimental conditions did not show a strong deviation (31 %-44 %). The percentage of skipping saccades was reduced to less than 5 % in conditions where texts were written against the reading direction (e.g., in mW and iW conditions) and between 10-15% in other conditions. Interestingly, half of the first-pass fixations observed in conditions where texts were written against reading direction came from refixation saccades, while only a third of first-pass fixations were generated from refixation saccades. Less than 12 % of fixations in reading manipulated text were moving backward (e.g., regression saccades) with the lowest observed in iW condition. When reading the manipulated texts for the first time, readers fixated on words, on average, about 53-137 ms longer and generated shorter saccades (5-6 character spaces for progressive saccades and 3 character spaces for regressive saccades) than those observed in reading normal text. Note that the mean fixation duration in sL condition is about 50 ms longer than those reported in the study reported by White et al. (2008). Global summary statistics from all sessions are presented in Table 2.2.

On a qualitative level, we compared the resulting saccade length distributions (Figure 2.2) with our hypotheses (Figure 2.1b). As expected, the distributions of the lengths of forward saccades during reading manipulated text are generally shifted to the left of those from the control condition, indicating a qualitatively shorter saccade length generated in the non-normal reading conditions. Furthermore, more regressive saccades were observed only in the reading mirrored-word (mW) and inverted-word (iW) conditions.

Single fixation duration and refixation probability

Results from statistical modeling using linear mixed-effects models for single fixation duration and refixation probability are summarized in Tables 2.3-2.5. For the specification of linear mixed-effects models, see section 2.8.

No significant word-length effect was observed in the single fixation duration measure for the control condition, which is in line with the finding reported in the study conducted by Kliegl et al. (2004). Compared to the control condition, word-based single fixation duration observed in all experimental conditions is significantly longer (t value > 2). For

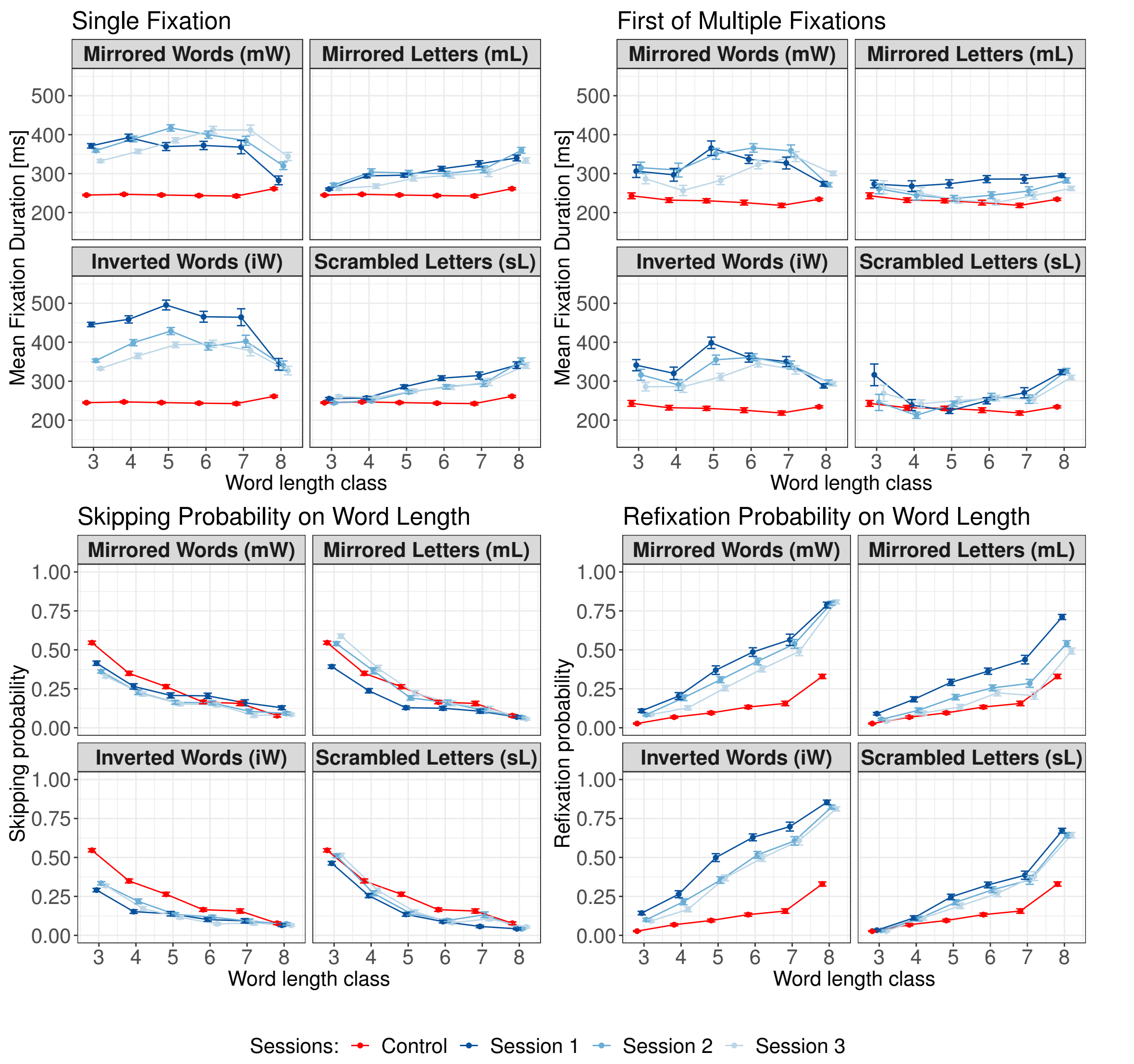


Figure 2.3: Fixation duration and probability measures as the function of word-length classes. *Upper row:* Mean fixation duration of single fixation (left) and first of multiple fixations as the function of word length classes. *Lower row:* Skipping (left) and refixation probabilities as the function of word length classes. Words with the length of fewer than three characters are grouped in word length class 3; long words (> 8 characters) are grouped in word length class 8. Error bars represent the standard error of the means. Red lines and dots represent data from reading normal text. The dark blue color represents data from the first experimental session. The lighter blue hues indicate data from the last two experimental sessions.

example, on medium words (5-7 characters), the estimated mean single fixation duration in the first experimental sessions was 48-104 ms longer than the value estimated in the control condition (238 ms). In line with the study reported by Kowler & Anton (1987), texts written against reading direction were more difficult to process. This processing difficulties seemed to be the property of the corresponding type of text manipulation and were more obvious after participants have learned how to read the texts. When readers fixated on medium-length words only once in the last experimental sessions, the fixation duration in mL (estimated mean: 309 ms) and sL (estimated mean: 326 ms) conditions were shorter compared to those observed in mW and iW conditions with estimated mean of 570 ms and 455 ms respectively.

Similar to single fixation measures, no significant word-length effect was observed in the fixation duration of the first of multiple fixations for the control condition. When words were fixated more than once, the duration of the first fixation in the sL condition (across all sessions) was significantly longer than in the control condition. In the mL condition, the duration of the first fixation was significantly longer than in the normal condition only in the first experimental session. After training, no significant difference was observed. Interestingly, in comparison to the control condition, the mean of first fixation duration was significantly longer in mW and iW conditions. For fixations on words with medium length, the estimated values for both conditions were about 90 ms longer than those estimated for the control condition. The difference remained significant even after training (estimated means session 3: $mW = 465.32$; $iW = 414.38$).

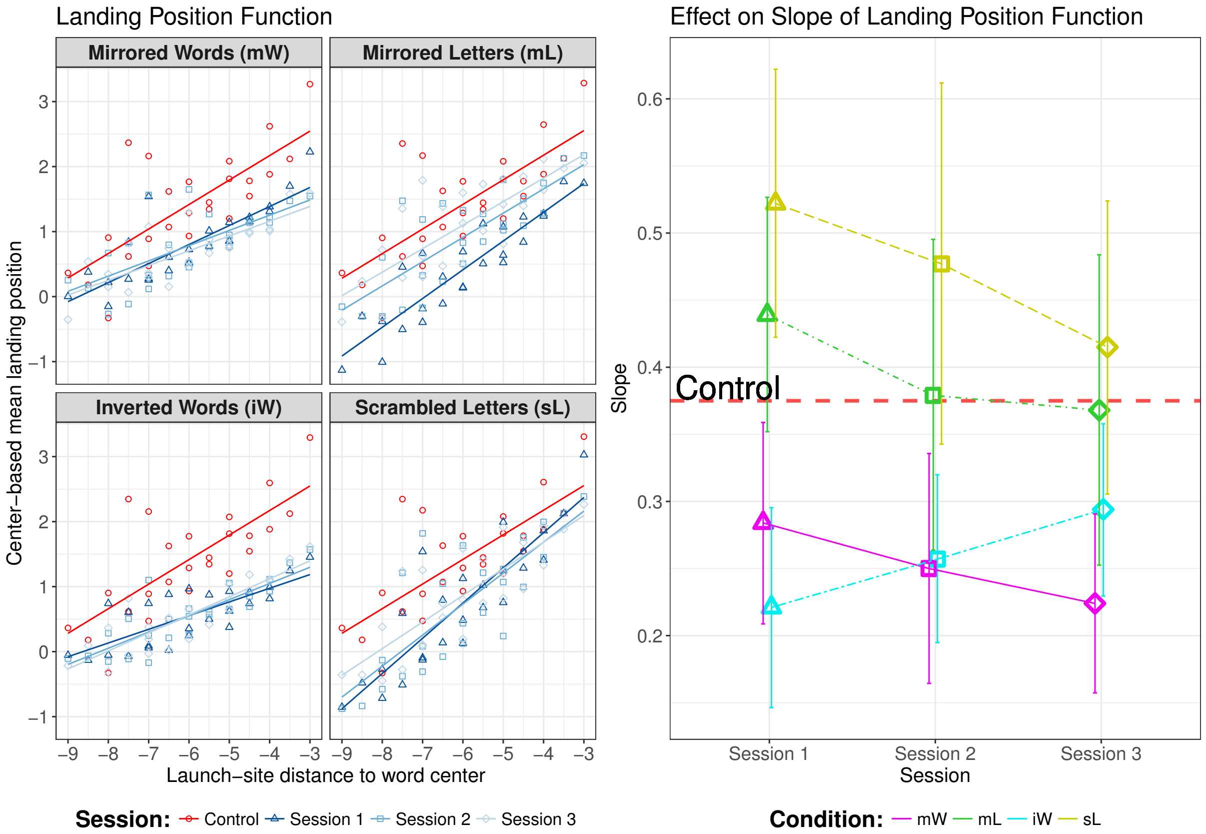
On the refixation probability measure, we replicated the word length effect in both control and experimental conditions (all $p < 0.01$). Long words were more likely to be re-fixated than short words. However, when the texts were manipulated, readers were more likely to fixate the words more than once. For example, the estimated refixation probability on medium words in the control condition was 0.16. However, readers in experimental conditions were twice more likely to fixate the words with the same lengths (estimated RFP: $mL = 0.42$; $sL = 0.65$; $mW = 0.44$; $iW = 0.56$). Interestingly, after training to read texts with words written against the reading direction (e.g., mW and iW conditions), readers almost always fixated on medium and long words more than once (estimated RFP above 0.87 in the third session).

Do these manipulations have something in common or do they generate different effects on fixation duration and probability measures presented above? The results from separate models which estimated the different effect size of manipulation types confirmed that some manipulation type generated greater effect than the others (see Table 2.6). All of the three models showed similar trends. The effect in mL condition was significantly different from control condition, but adding the effect from sL condition to the mean of the two conditions (control and mL conditions) did not yield a significant gain on effect size. However, adding the effect from mW condition and iW conditions yielded significant gains on the effect size. The results from various measures showed that of all manipulation types tested in the current study, the iW condition generated the largest effect.

The effects of word length on the duration of single fixation and first of multiple fixations, as well as on skipping and refixation probabilities are visualized in Figure 2.3.

2.3.2 Landing positions distributions and launch-site effect

A first glance at the resulting distributions for within-word landing positions indicates differences between normal reading and manipulated texts (Appendix 2.10-2.11). Except



(a) (b)

Figure 2.4: Analysis of the launch-site effect on the systematic error component. (a) Landing position function: Mean center-based landing position as a function of center-based launch-site distance across all sessions. Red lines and dots represent data from the normal reading session. Data from the first experimental sessions are presented in a dark blue color. The lighter blue hues represent the last two experimental sessions. (b) The estimated slope parameter λ (and the 95 % confidence interval) over the course of training in the experimental conditions. The red horizontal dashed line represents the estimated slope for reading normal text (baseline). Results for reading mirrored words (mW) and inverted words (iW) are presented with magenta and cyan lines, resp. Green and yellow lines represent estimations for reading texts with mirrored letters (mL) and scrambled letters (sL).

for short words (i.e., word length up to 4 letters), we found increased leftward shifts across all experimental conditions. Stronger shifts in the mirrored-word (mW) and inverted-word (iW) conditions were observed, in comparison to the other two conditions (mL, sL). Since saccades observed in the experimental conditions were shorter than those observed in the control condition, we analyzed only saccades that were launched up to 5 characters away from the word beginning. As a result, more overshoots were reported in this study. Undershoots were typically observed for saccades launched further than 7 characters away and more prominent for observations on long words (McConkie et al., 1988; Nuthmann et al., 2005; Krügel & Engbert, 2010). Based on Bayesian fits of the distribution (see Section 2.8), we obtained mean landing positions that were used for further analyses.

In Figure 2.4a, center-based mean landing sites are plotted against center-based launch sites for forward saccades and different lengths of the target words. The slope parameters from landing position functions are plotted for all sessions in Figure 2.4b. The estimated slope of ($\lambda_0 = 0.37$) was observed in reading normal text. Compared to the value from control condition, both conditions iW ($\lambda_1 = 0.31$,$\lambda_2 = 0.25$,$\lambda_3 = 0.23$) and mW ($\lambda_1 = 0.24$, $\lambda_2 = 0.26$, $\lambda_3 = 0.29$) generated shallow slopes, which indicates a tendency to reduced oculomotor control. In contrast, conditions mL ($\lambda_1 = 0.44$, $\lambda_2 = 0.38$, $\lambda = 0.37$) and sL ($\lambda_1 = 0.52$, $\lambda_2 = 0.48$, $\lambda = 0.41$) generated greater slope values (λ) compared to reading normal text, indicating a tendency to increased oculomotor control. Interestingly, except in the mW condition, the λ values approach the value of normal reading after training.

In the Bayesian model, the slope parameter λ represents the strength of oculomotor control *and* the relation between the observational error of the target location (σ_0^2) and the standard deviation of the prior distribution (σ_T^2). In extreme cases, a value of slope near to 0, where $\sigma_0^2 \rightarrow 0$, the eyes always land on the target (i.e., the word center) regardless of where the saccade started. In the other extreme case, the slope value of $\lambda \rightarrow 1$ indicates the absence of a target selection process in saccade planning, so that the eyes generate random constant saccade lengths (from a uniform distribution). Therefore, our data show that saccades from reading text composed of words with reversed letter sequences (i.e., mW and iW) tend to land precisely on the target location (word center) on average, while readers of manipulated texts with normal letter order (i.e., mL and sL) tend to generate saccades with similar lengths. Comparing the results with our hypotheses, there is no dramatic effect of a shift of the mean landing position toward the word ends. Therefore, we ran post-hoc analyses for single and two-fixation cases in the next section.

Additionally, we also considered saccadic precision in word-to-word forward saccades. Figure 2.5 shows the standard deviations of landing positions in normal reading and in reading with manipulated text as a function of launch-site distance. The main effect on standard deviation (σ_{SF}) of within-word landing positions of fixations coming from word-to-word forward saccades yielded an F-ratio of $F[1, 198] = 33.8$,$p < 0.000$, indicating a significant difference between reading normal text (M=1.85,SD=0.30) and manipulated text (M=1.54,SD=0.36). Most importantly, it turned out that the variance of landing-position distributions in all experimental conditions with manipulated texts are lower compared to normal reading. Thus, reading under manipulated text conditions led to increased overall precision of readers' saccades.

2.3.3 Landing positions for single vs. two-fixation cases

The manipulation of text displays resulted in the changes of the proportion of cases where words were fixated only once, twice, or multiple times (see Table 2.1 for summary). Under normal reading condition, most words were fixated only once (85 %); some words were fixated exactly twice (14 %) and a few words received multiple fixations (2 %). When readers were first confronted with manipulated texts, however, the observed single fixation

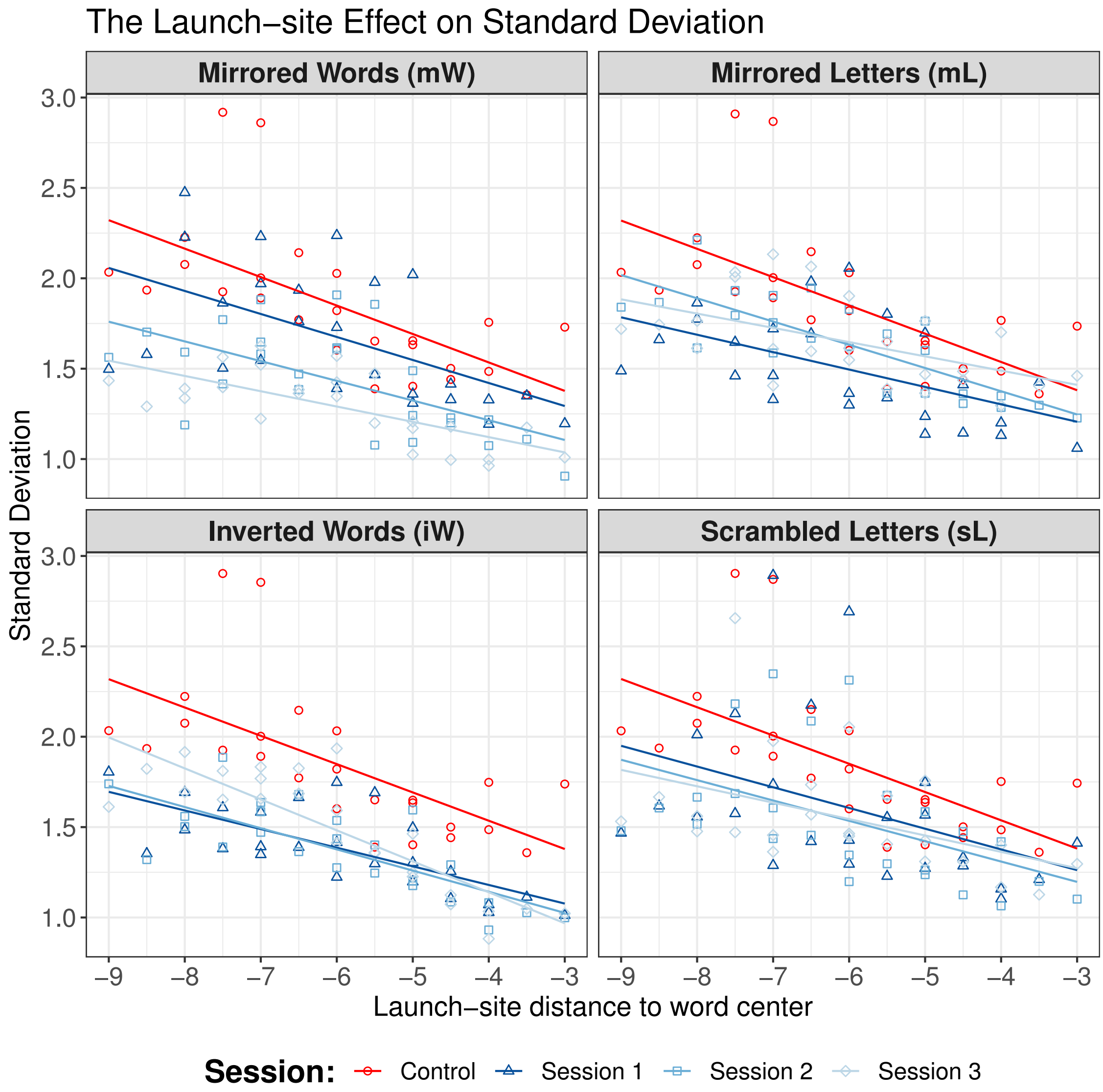


Figure 2.5: The launch-site effect on the standard deviations of the distributions of within-word positions for fixations coming from word-to-word forward saccades. Red lines and dots represent data from the normal reading session. Data from the first experimental sessions are presented in dark blue color. The lighter blue hues represent the last two experimental sessions.

cases were reduced to about 58 % to 74 %. About 20 % of two-fixation cases and 12 % of multiple-fixation cases were observed in the first non-normal reading sessions.

Single fixation cases. Only cases where exactly one fixation land on a word were considered for this analysis. Relative frequency of fixation landing position were calculated based on word length. To obtain estimates for the mean μ_{SF} and standard deviation σ_{SF} for the landing position distribution of each word length, a grid search method (in steps of 0.01) with a minimum-χ^2 criterion was applied. Analysis of variance was conducted to statistically compare the manipulation effects on mean (μ_{SF}) and standard deviation (σ_{SF}) of landing position distributions.

No significant difference was observed for the mean (μ_{SF}) of the landing position distribution of single fixation cases between control and experimental conditions ($F[1, 30] =$

Table 2.1: Relative frequency of single, two-fixation and multiple-fixation cases [in %]

Condition	Session	Single fixation	Two-fixation	Multiple fixation
Control	0	84.21	13.82	1.97
Mirrored-Word (mW)	1	63.29	20.4	16.31
	2	66.39	19.66	13.95
	3	67.72	18.39	13.89
Mirrored-Letter (mL)	1	71.41	21.04	7.56
	2	74.97	20.39	4.64
	3	78.56	17.33	4.11
Inverted-Word (iW)	1	58.18	21.99	19.83
	2	61.98	21.97	16.05
	3	61.54	22.1	16.36
Scrambled-Letter (sL)	1	74.13	18.24	7.63
	2	74.3	17.82	7.87
	3	72.87	19.3	7.83

2.364, $p = 0.135$). The main effect on standard deviation (σ_{SF}) of within-word landing position distribution of single fixation cases yielded an F-ratio of $F[1, 30] = 32.7$,$p < 0.000$, indicating a significant difference between reading normal text (M=2.95,SD=0.84) and manipulated text (M=1.51,SD=0.55). When words were fixated only once, readers' mean landing position did not change across the manipulation types. However, the precision of saccades landing on a selected target word increased as the text display deviated from the normal presentation.

Among our key results is that the two conditions where the word beginnings were located at the end of the manipulated word strings (i.e., conditions mW and iW) produced only a slight shift of the average landing position. This finding turned out to be robust and remained observable even after training. Figure 2.6 presents data for single fixations. The finding did not support our hypothesis that readers targeted the second half of the word strings during reading mirrored-word (mW) and inverted words (iW). On a qualitative level, there is little adaptivity of the oculomotor system.

Since in our hypothesis, an initial saccade toward the second half of the word would require an additional refixation in the first half of the word, we ran a post-hoc analysis of all two-fixation cases. The corresponding plot in Figure 2.7 presents data for the initial landing position (first saccade into the word) from all cases, where the word was fixated exactly two times. In contrast to typical OVP effect on refixation probability, plotting the initial of two fixations will give us a better understanding of word targeting in saccade planning.

Two-fixation cases. For this analysis, we considered cases when exactly two fixations on a word were observed. The landing position distribution of the initial fixation was fitted to a quadratic polynomial, i.e.,

$$y = A + B \cdot L(x - C)^2, \tag{2.5}$$

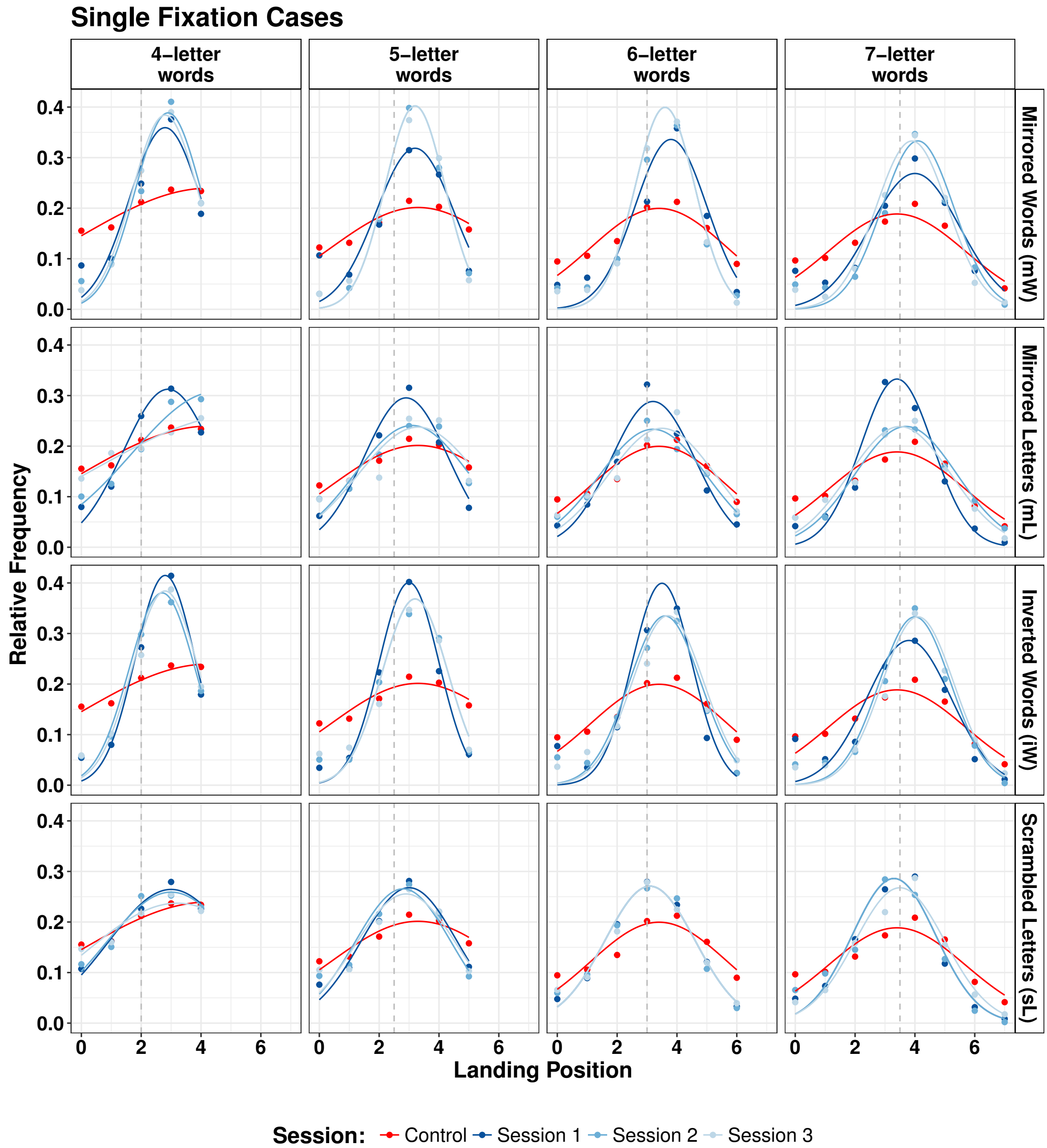


Figure 2.6: Within-word landing position distributions for single-fixation cases. Columns relate to different word lengths. Rows refer to experimental manipulations. Different colors indicate the control condition (red) and the experimental conditions (blue hues).

where x denotes the initial landing position and y is the relative frequency of the fixation. The parameter A represents the actual relative frequency of the initial landing position. The parameter B is the slope of the parabolic curve, representing the within-word maximum or minimum relative frequency of the landing position. The parameter C reflects within-word position where the relative frequency was at the minimum or maximum, depending on the value of parameter B. In general, the value of the parameter B is assumed to be positive, resulting in a distribution of landing position qualitatively similar to the optimal viewing position (OVP) curve but with different interpretation: when a word is fixated exactly twice, the initial fixations tend to be near word edges more often than on the word center. The estimation of the three parameters representing the characteristics of the landing position of the first of two fixation cases was conducted based on a maximum likelihood method using the bbmle package (Bolker, 2017) for R studio. The estimated parameters are summarized in Table 2.7-2.11.

Under the normal reading condition, refixational saccades are mainly launched from initial fixations near the word beginning with a subsequent secondary fixation further into the word (most refixations are directed toward reading direction). Similar patterns were observed in the condition where manipulated texts were written in the typical direction from left to right (mL and sL). However, in the two conditions (mW and iW) with reversed letter sequences, the initial landing positions deviated from those of normal reading (for detailed estimated parameters, see Table 2.8 and 2.10). When a word was fixated more than once, the first saccade landed mostly behind the location of the word center in the second half of the word strings. The effect was stronger for longer words (see Figure 2.7). This finding matches our initial hypothesis that readers direct the eyes at first into the second half of the reversed words and then generate a secondary within-word saccades along writing direction. However, as we found no support of an overall shift of all initial saccades for the conditions mW and iW in our previous analyses, a possible explanation of the observed shift in the initial landing positions of two-fixation cases is a strategic modulation of readers' within-word targeting process.

2.4 Discussion

Natural text reading requires efficient coordination of cognitive and oculomotor control processes. Cognitive principles are essential for the selection of an upcoming target word, however, it is the oculomotor system that provides the machinery to move the gaze to the region of the identified target word. In the current study, we set out to investigate whether ongoing cognition is able to overwrite default oculomotor control when the reader is confronted with manipulated (mirrored-reversed, inverted, and scrambled) text layouts.

On a global level, changing the display and positions of letters in a word modulates eye-movement statistics. We observed a longer average fixation duration and shorter mean saccade amplitude in reading conditions with non-normal text layout. These findings support the conclusion from previous studies (Kowler & Anton, 1987; Rayner et al., 2006) that changes on the level of letters lead to increased costs for word recognition in comparison to reading normal text. Interestingly, similar to findings from previous studies (Kowler & Anton, 1987; Kolers & Perkins, 1975), orthographic manipulations from our current study can be grouped into two categories based on their writing directions. Difficulties increased dramatically when readers read texts written against the reading

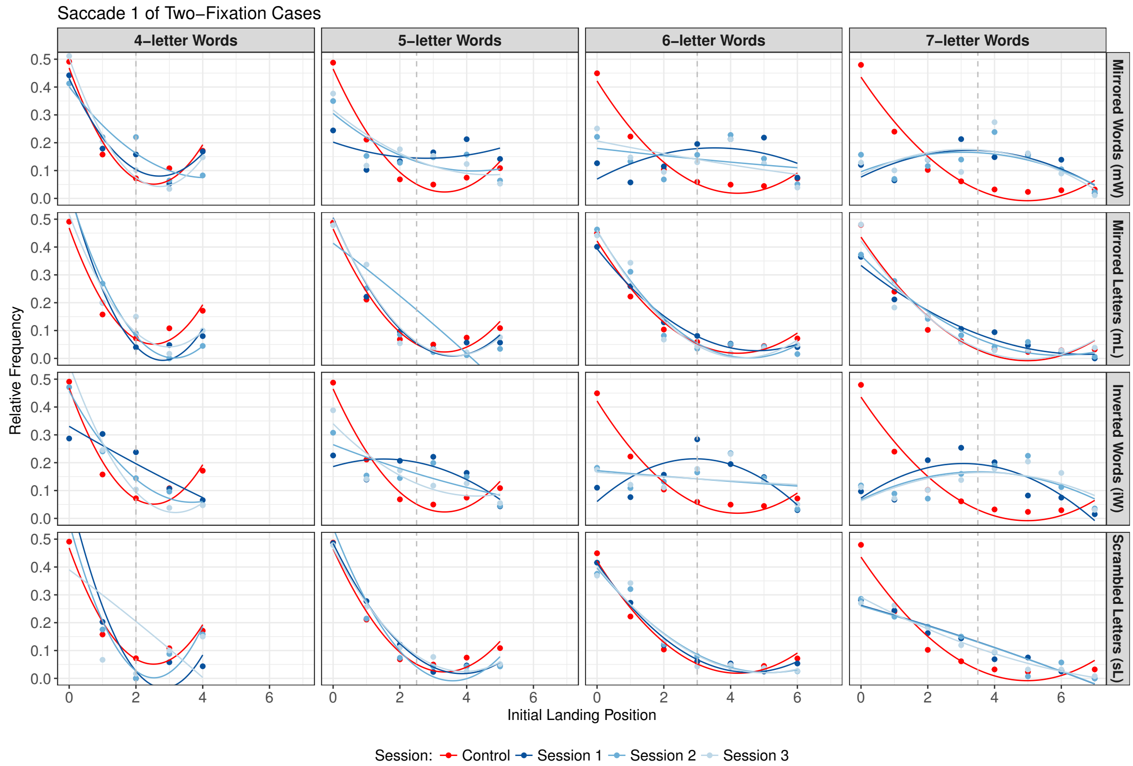


Figure 2.7: Within-word landing positions for the initial landing position (first saccade) in two-fixation cases. Red dots and curves represent the fixations observed in the control condition. Blue hues represent the fixations observed in experimental conditions.

direction as in mirrored words (mW) and inverted words (iW) conditions, where the letter-sequence of words is written from right to left within the displayed strings due to mirroring or inversion. Our interpretation is supported by the fact that the observed deviations remained stable even after training. In contrast, during the manipulations that kept the letter-sequence in the reading direction (i.e., from left to right) in mirrored-letter word (mL), the patterns observed in eye movement measures (e.g., word-length effect) remained similar to those of normal reading and, after training, approached the behavior observed in normal reading. Finally, in our fourth experimental condition, we analyzed the eye movement patterns during the reading text composed of scrambled-letter (sL) words. Since letters in a word were randomly scrambled, there was no systematic way that the oculomotor behavior could adapt to process the new text layout.

One of our motivations to run the current study was to obtain a detailed picture of within-word landing positions as the most important signature for oculomotor control. Mean landing position distribution of single fixations in reading manipulated texts does not significantly differ from reading normal text, although there was a slight shift observed in mirrored words (mW) and inverted words (iW) conditions. However, readers tend to increase their precision in landing on word center when texts presentation was manipulated. Increased saccadic precision was found for word-to-word forwards saccades in all experimental conditions compared to normal reading and the result also holds, if only single-fixation cases were considered. The finding supports the idea that word center serves as the saccadic target location (Engbert & Krügel, 2010). Analysis of mean landing position of forward saccades based on different launch sites demonstrated a general left shifts in experimental conditions compared to those observed in control condition. Especially in conditions where words are written against reading direction such as in mW and iW conditions, there is no clear preference for the eyes to initially land in the second half of the word strings (where the beginning of a word is located in this manipulation). This is contrary to our hypothesis. Interestingly, the peaks of the landing position in all manipulation types were shifted toward word centers, not necessarily toward the beginning of word strings, compared to the peaks observed in reading normal text. In some rare undershoot cases in our data (e.g., launch site: -4, word length: 7 in iW and mW conditions), the peaks in experimental condition shift rightward of the peak observed in reading normal text. Furthermore, the variance of the initial landing position distribution was much smaller, meaning that the eyes landed more precisely on the word center, which served as the theoretical target position. Given the precision of the landing position distributions and the highest likelihood to land on word center, we speculate that the leftward shifts were moving towards the word centers, not the word beginnings. Regarding the generally improved precision of landing position distributions, a possible explanation is that with longer average fixation durations under our manipulations, the oculomotor system had more time to prepare the next saccade, which could result in a reduced saccadic error (McConkie et al., 1988). An alternative explanation is that an unusual presentation of text was more salient and popped up parafoveally to enable precise saccadic targeting (Hyönä, 1995).

Additionally, modulation of manipulation types on the launch-site effect was observed. In conditions where texts were written against reading direction (from right to left), we observed a reduced launch-site effect, while an increased launch-site effect was observed in conditions where texts were written normally. However, we are not sure if the difference in the effect size is caused by the change in reading direction or increased processing difficulties. The findings could be explained in the theoretical framework of a Bayesian model of sensorimotor integration that we applied to the oculomotor control during reading (Engbert & Krügel, 2010; Krügel & Engbert, 2014). According to Bayes' rule, the observed landing position distribution is the posterior distribution in a sensorimotor transform based on prior knowledge of typical target positions. If we assume that the prior knowledge is uninformative under unfamiliar text layout, then the posterior distribution would shift toward the likelihood distribution, which is assumed to be unbiased with respect to the target word center. Therefore, in the Bayesian model, we could have expected a more centered landing-position distribution if we assumed that the experimental manipulations induce less prior knowledge on the possible target positions. Our finding demonstrated that by simply changing the letter-sequence information of words, we could obtain estimations for the slope parameter λ other than the typical value of 0.5. As a consequence, reading models development should aim for integrating a process-oriented model in generating saccade lengths.

The most striking finding in the current study is the effect of orthographic manipulation on the initial landing position of two-fixation cases. When a word shows reversed letter ordering (hence a change in their spatial information) as a consequence of the experimental manipulation, we observed a clear shift into the second half of the word string when two fixations were generated. This finding suggests that the oculomotor system is able to adapt to display changes. Given that our hypothesis requires more than two fixations, analyzing the initial landing positions in refixation cases is more reasonable to test the hypothesis.

Furthermore, our study also demonstrates that the typical usage of mean fixation position as a dependent variable to characterize oculomotor control is not specific enough to characterize control processes underlying reading. Since reading is a complex process, data delivered are usually complicated and require various analysis methods and inferences. Further systematic analyses and advanced mathematical modeling are required to investigate the dynamical processes underlying principles of oculomotor control and their interaction with ongoing cognition during reading.

2.5 Acknowledgments

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2.6 Author contributions

R.E. and A.K. developed the study concept and the study design. Testing and data collection were performed by J.C.. J.C. and A.K. performed the data analysis and all authors contributed to the interpretation. J.C. and A.K. drafted the manuscript, and R.E. provided critical revisions. All authors approved the final version of the manuscript for submission.

2.7 Additional information

Competing interests The authors declare no competing financial and/or non-financial interests.

2.8 Appendix: Supplementary information

Global summary statistics

Statistics of fixation durations and saccade lengths of all valid fixations were computed for a global summary analysis. Words are categorized based on their length (WLC): short ($\leq$ 4 characters), medium (5-7 characters), and long ($\geq$ 8 characters) for further statistical analysis.

Fixation durations. One way to quantify the visual information processing in reading is to examine the time spent on fixating words (fixation duration). Single fixation duration (SFD) refers to the time spent on a word that received exactly one fixation. When a word received more than one fixations in first-pass reading, the duration of the first and second fixations generated the first of multiple fixations duration (FMD) and second of multiple fixation duration (SMD). Inspection of duration distributions suggested that log-transformation is required to meet the assumptions of the Linear-Mixed Model. Therefore, for word-length effect analysis, the fixation duration measures were transformed into their logarithmic values.

Fixation probability. The fixation probability of a word depends on different saccade types. For first-pass reading data, we computed the skipping, refixation and regression probabilities. Regression cases were counted for words whose saccade directions went against overall reading directions. For each word that is the target of skipping saccades and refixations and/or source of regression saccades, a logical value of 1 is assigned to the word. Otherwise, a logical value of 0 was assigned.

The coefficients of the fixed effect of word length classes and the random effect for various participants and sentences were estimated using the *lme4* package (Bates et al., 2015). Each independent variable of fixation duration and fixation probability measure is modeled as a function of word length (`WLC`) across sessions (`sess`), with a fully parameterized variance-covariance matrix for participants expressed in the term of `pID`. Furthermore, the variance for the intercept over sentence number (expressed in the terms (1|`sID`)) is taken into account. The model also allows us to examine the interaction of the word-length effect between the control and experimental sessions. For instance, the log-transformed duration of the first of multiple fixations(`FMD`) is modeled as

$$\mathtt{lmer}(\log(\mathtt{FMD}) = \mathtt{WLC} * \mathtt{sess} + (1 + \mathtt{WLC} + \mathtt{sess}|\mathtt{pID}) + (1|\mathtt{sID})). \quad (2.6)$$

Likewise, refixation probability (RFP) is modeled as

$$\mathtt{glmer}(\mathtt{RFP} = \mathtt{WLC} * \mathtt{sess} + (1 + \mathtt{WLC} + \mathtt{sess}|\mathtt{pID}) + (1|\mathtt{sID})). \quad (2.7)$$

Note that the models for fixation probabilities were estimated using the general function of `glmer()` due to its ability to statistically analyze data with binary outcome. All models were estimated based on restricted maximum likelihood (REML).

Initial landing position

Within-word landing positions observed during reading are widely distributed and sometimes extend to the neighboring words. Observations of word-based landing positions in reading experiments are typically truncated at word boundaries (McConkie et al., 1988; Engbert & Nuthmann, 2008). To obtain estimations of the means and standard deviations of the landing-position distributions, truncated Gaussian curves for distributions of word-based fixation positions were fitted using Bayesian parameter inference (Kruschke, 2014) available in the package *rjags* (Plummer, 2016) in the R environment.

Only fixations from inter-word forward saccades were considered in the estimation procedure. For each session, fixation data were grouped based on word length (3-7 letters) and launch-site distance (-1 to -5 characters), resulting in three different word-length and launch-site session-specific data subsamples. For each data subset S_i, a two-dimensional posterior distribution was estimated over the parameters mean μ and standard deviation σ of the underlying Gaussian landing-position distribution conforming to

$$p(\mu, 1/\sigma^2|S_i) = \frac{p(S_i|\mu, 1/\sigma^2)p(\mu, 1/\sigma^2)}{\int\int p(S_i|\mu, 1/\sigma^2)p(\mu, 1/\sigma^2)\,\mathrm{d}\mu\mathrm{d}1/\sigma^2}\,. \tag{2.8}$$

Observations of fixation landing positions are assumed to be generated by a normal-density likelihood function $p(S_i|\mu, 1/\sigma^2)$ with mean μ and precision $\tau = 1/\sigma^2$. With $p(\mu, 1/\sigma^2)$ we specified a normally distributed prior on the mean μ with mean M and precision T and a prior on τ distributed as a gamma density distribution with shape parameter A and rate B (see Kruschke, 2014). The parameters M, T (for the prior over μ) and A,B (for the prior τ) were derived as follows: For the control condition, distributions of landing positions for each word length and launch-site distance were independently fitted by a truncated Gaussian function and the parameters of these fits were used to estimate the parameters of the empirical prior distribution. The estimated parameters from the control condition were used to estimate landing position distributions for the first experimental session and the resulting parameters were used to systematically update the prior distribution for the second experimental session.

Tables & Figures

Table 2.2: Global summary statistics.

Condition		Control	Mirrored Words (mW)			Mirrored Letters (mL)			Inverted Words (iW)			Scrambled Letters (sL)		
Session		0	1	2	3	1	2	3	1	2	3	1	2	3
Detected fixations	N	82487	21598	27500	26957	26677	24205	22246	22531	24104	25728	25549	26648	24062
Discarded fixation	N	40377	10351	12251	11691	12143	11639	11271	10340	10766	10933	11361	11350	10597
	%	48.95	47.93	44.55	43.37	45.52	48.09	50.67	45.89	44.66	42.49	44.47	42.59	44.04
Valid fixation	N	42110	11247	15249	15266	14534	12566	10975	12191	13338	14795	14188	15298	13465
	%	51.05	52.07	55.45	56.63	54.48	51.91	49.33	54.11	55.34	57.51	55.53	57.41	55.96
First-pass fixation	N	32343	6925	11166	11620	11200	10061	8809	9479	10428	11912	10269	10034	8836
	%	76.81	61.57	73.22	76.12	77.06	80.07	80.26	77.75	78.18	80.51	72.38	65.59	65.62
Forward saccades	N	14956	2960	5386	5725	5636	4379	3909	4050	4653	5363	4887	4219	3843
	%	46.24	42.74	48.24	49.27	50.32	43.52	44.38	42.73	44.62	45.02	47.59	42.05	43.49
Skipping saccades	N	9963	516	834	931	1476	2193	1964	431	674	774	1973	1999	1807
	%	30.8	7.45	7.47	8.01	13.18	21.8	22.3	4.55	6.46	6.5	19.21	19.92	20.45
Refixations	N	7357	3436	4933	4957	4082	3486	2930	4989	5096	5772	3400	3805	3170
	%	22.75	49.62	44.18	42.66	36.45	34.65	33.26	52.63	48.87	48.46	33.11	37.92	35.88
Regressions	N	3692	693	808	854	734	695	638	549	584	649	992	985	966
	%	11.42	10.01	7.24	7.35	6.55	6.91	7.24	5.79	5.6	5.45	9.66	9.82	10.93
fixation duration	mean [ms]	245	354	351	337	299	277	266	383	344	329	306	300	304
forward saccade amplitude	mean [char]	7.82	5.19	5.58	5.81	5.53	6.56	6.86	5.25	5.55	5.81	6.18	6.15	6.38
backward saccade amplitude	mean [char]	4.23	2.82	2.97	3.03	3.01	2.88	2.67	2.63	2.57	2.79	4.66	3.95	4.25

Table 2.3: Results from Linear Mixed-Effects: Single Fixation Duration

Condition		*b*	*SE*	*t value*
Mirrored Letters (mL)	Intercept	5.47	0.04	124.53
	WLC	0.02	0.02	**1.15**
	Session 1	0.18	0.02	9.69
	Session 2	0.10	0.02	5.32
	Session 3	0.09	0.02	4.22
	WLC:Session 1	0.06	0.01	7.79
	WLC:Session 2	0.07	0.01	9.38
	WLC:Session 3	0.06	0.01	8.30
Mirrored Words (mW)	Intercept	5.44	0.04	142.66
	WLC	0.02	0.02	**0.87**
	Session 1	0.31	0.07	4.54
	Session 2	0.31	0.06	5.11
	Session 3	0.29	0.06	5.10
	WLC:Session 1	-0.14	0.01	-12.13
	WLC:Session 2	-0.07	0.01	-7.08
	WLC:Session 3	-0.01	0.01	**-0.99**
Inverted Words (iW)	Intercept	5.48	0.04	128.67
	WLC	0.01	0.02	**0.45**
	Session 1	0.36	0.05	7.48
	Session 2	0.27	0.03	7.84
	Session 3	0.22	0.03	6.17
	WLC:Session 1	-0.21	0.01	-18.10
	WLC:Session 2	-0.10	0.01	-9.56
	WLC:Session 3	-0.06	0.01	-5.71
Scrambled Letters (sL)	Intercept	5.46	0.03	186.58
	WLC	0.01	0.02	**0.24**
	Session 1	0.11	0.04	2.91
	Session 2	0.11	0.05	2.21
	Session 3	0.10	0.04	2.34
	WLC:Session 1	0.10	0.01	11.95
	WLC:Session 2	0.12	0.01	14.61
	WLC:Session 3	0.09	0.01	10.80

Note: Fixation duration value is log-transformed. WLC = word length. Non-significant values are marked in bold.

Table 2.4: Results from Linear Mixed-Effects model: Duration of First of Multiple Fixations

Conditions		*b*	*SE*	*t value*
Mirrored Letters (mL)	Intercept	5.43	0.05	114.86
	WLC	-0.01	0.02	**-0.31**
	Session 1	0.16	0.03	4.56
	Session 2	0.04	0.03	**1.23**
	Session 3	0.03	0.03	**0.93**
	WLC:Session 1	0.09	0.01	6.04
	WLC:Session 2	0.09	0.02	5.86
	WLC:Session 3	0.08	0.02	4.68
Mirrored Words (mW)	Intercept	5.37	0.05	101.59
	WLC	0.04	0.03	**1.56**
	Session 1	0.34	0.04	9.23
	Session 2	0.32	0.03	10.98
	Session 3	0.24	0.05	4.36
	WLC:Session 1	-0.16	0.02	-10.31
	WLC:Session 2	-0.20	0.01	-14.05
	WLC:Session 3	-0.10	0.01	-6.60
Inverted Words (iW)	Intercept	5.46	0.04	122.19
	WLC	0.03	0.02	**1.22**
	Session 1	0.33	0.05	6.32
	Session 2	0.25	0.05	4.83
	Session 3	0.20	0.05	4.14
	WLC:Session 1	-0.16	0.02	-10.58
	WLC:Session 2	-0.14	0.02	-9.11
	WLC:Session 3	-0.11	0.02	-7.32
Scrambled Letters (sL)	Intercept	5.44	0.03	162.02
	WLC	0.01	0.02	**0.27**
	Session 1	0.06	0.04	**1.54**
	Session 2	0.06	0.03	**1.84**
	Session 3	0.06	0.03	**1.77**
	WLC:Session 1	0.15	0.02	8.80
	WLC:Session 2	0.22	0.02	12.83
	WLC:Session 3	0.15	0.02	8.52

Note: Fixation duration value is log-transformed. WLC = word length. Non-significant values are marked in bold.

Table 2.5: Results from Linear Mixed-Effects model: Refixation Probabilities

Condition		*b*	*SE*	*z value*	*Pr(>|z|)*
Mirrored Letters (mL)	Intercept	-1.63	0.12	-13.75	0.000
	WLC	1.15	0.09	12.52	0.000
	Session 1	1.29	0.18	7.32	0.000
	Session 2	0.76	0.14	5.53	0.000
	Session 3	0.48	0.17	2.75	0.006
	WLC:Session 1	0.37	0.05	6.86	0.000
	WLC:Session 2	0.41	0.06	7.33	0.000
	WLC:Session 3	0.38	0.06	6.48	0.000
Mirrored Words (mW)	Intercept	-1.35	0.18	-7.62	0.000
	WLC	1.15	0.11	10.50	0.000
	Session 1	1.39	0.23	6.15	0.000
	Session 2	1.35	0.14	9.78	0.000
	Session 3	1.19	0.21	5.71	0.000
	WLC:Session 1	0.55	0.05	10.00	0.000
	WLC:Session 2	0.64	0.05	12.98	0.000
	WLC:Session 3	0.69	0.05	13.85	0.000
Inverted Words (iW)	Intercept	-1.51	0.17	-9.03	0.000
	WLC	1.21	0.07	18.14	0.000
	Session 1	1.87	0.15	12.49	0.000
	Session 2	1.69	0.17	10.06	0.000
	Session 3	1.65	0.17	9.98	0.000
	WLC:Session 1	0.64	0.05	11.76	0.000
	WLC:Session 2	0.52	0.05	9.96	0.000
	WLC:Session 3	0.62	0.05	12.17	0.000
Scrambled Letters (sL)	Intercept	-1.51	0.15	-9.73	0.000
	WLC	1.46	0.10	13.95	0.000
	Session 1	0.78	0.23	3.48	0.000
	Session 2	0.57	0.20	2.90	0.004
	Session 3	0.67	0.18	3.64	0.000
	WLC:Session 1	0.32	0.05	5.92	0.000
	WLC:Session 2	0.42	0.06	7.61	0.000
	WLC:Session 3	0.31	0.06	5.52	0.000

Note: WLC = word length. Non-significant values are marked in bold.

Table 2.6: Results from Linear Mixed-Effects model: Effect sizes across manipulation types

Measures		*b*	*SE*	*z value*	*Pr(>|z|)*
Single Fixation Duration (SFD)	Intercept	5.65	0.03	213.36	
	WLC	-0.03	0.01	-3.57	
	mL	0.09	0.02	3.95	
	sL	0.01	0.02	**0.46**	
	mW	0.05	0.01	3.90	
	iW	0.04	0.01	4.07	
	WLC:mL	0.03	0.00	6.97	
	WLC:sL	0.02	0.00	8.38	
	WLC:mW	-0.05	0.00	-19.63	
	WLC:iW	-0.04	0.00	-19.74	
First of Multiple Fixations duration (FMF)	Intercept	5.60	0.03	212.41	
	WLC	0.00	0.01	**-0.29**	
	mL	0.08	0.02	4.08	
	sL	-0.01	0.01	**-0.42**	
	mW	0.06	0.01	5.47	
	iW	0.04	0.01	4.45	
	WLC:mL	0.04	0.01	5.82	
	WLC:sL	0.05	0.01	9.21	
	WLC:mW	-0.06	0.00	-17.12	
	WLC:iW	-0.04	0.00	-14.35	
Refixation Probability (RFX)	Intercept	-0.40	0.08	-5.03	0.000
	WLC	1.59	0.04	36.17	0.000
	mL	0.62	0.08	7.33	0.000
	sL	0.04	0.06	0.66	**0.506**
	mW	0.21	0.04	4.80	0.000
	iW	0.21	0.04	5.91	0.000
	WLC:mL	0.17	0.02	7.17	0.000
	WLC:sL	0.08	0.02	4.47	0.000
	WLC:mW	0.07	0.01	5.05	0.000
	WLC:iW	0.05	0.01	4.54	0.000

Note: LMM model with helmert contrast. SFD and FMD values are log-transformed (base 10).
WLC = word length. Non-significant values are marked in bold.

Table 2.7: Quadratic fit to initial landing position curve (two-fixation cases) for reading normal text: Estimates of parameters A, B and C

Session	Word Length	Parameters	Estimate	Std. Error	z value	Pr(z)
0	4	A	0.051	0.020	2.466	0.013
	4	B	0.065	0.008	7.814	0.000
	4	C	2.528	0.101	24.916	0.000
	5	A	0.023	0.015	1.497	0.134
	5	B	0.040	0.004	9.139	0.000
	5	C	3.336	0.121	27.468	0.000
	6	A	0.019	0.012	1.516	0.130
	6	B	0.023	0.003	8.859	0.000
	6	C	4.21	0.168	25.043	0.000
	7	A	-0.008	0.016	-0.518	0.604
	7	B	0.018	0.003	7.115	0.000
	7	C	4.98	0.251	19.834	0.000

Table 2.8: Quadratic fit to initial landing position curve (two-fixation cases) for reading ***mirrored-word (mW)*** text: Estimates of parameters A, B and C

Session	Word Length	Parameters	Estimate	Std. Error	z value	Pr(z)
1	4	A	0.080	0.022	3.684	0.000
	4	B	0.048	0.009	5.309	0.000
	4	C	2.670	0.173	15.650	0.000
	5	A	0.144	0.027	5.288	0.000
	5	B	0.007	0.007	1.037	0.300
	5	C	2.787	0.757	3.684	0.000
	6	A	0.181	0.028	6.533	0.000
	6	B	-0.009	0.005	-1.680	0.093
	6	C	3.523	0.602	5.852	0.000
	7	A	0.173	0.019	9.009	0.000
	7	B	-0.009	0.003	-3.265	0.001
	7	C	3.267	0.314	10.392	0.000
2	4	A	0.074	0.039	1.897	0.058
	4	B	0.019	0.010	1.9497	0.051
	4	C	4.152	1.145	3.627	0.000
	5	A	0.099	0.027	3.633	0.000
	5	B	0.012	0.008	1.518	0.129
	5	C	4.202	1.221	3.443	0.001
	6	A	0.056	0.086	0.650	0.516
	6	B	0.000	0.000	1.049	0.294
	6	C	17.788	0.000	38076.98	0.000
	7	A	0.166	0.025	6.692	0.000
	7	B	-0.007	0.004	-2.078	0.038
	7	C	3.057	0.526	5.806	0.000
3	4	A	0.043	0.011	3.861	0.000
	4	B	0.063	0.005	13.502	0.000
	4	C	2.718	0.069	39.444	0.000
	5	A	0.0845	0.042	1.998	0.046
	5	B	0.011	0.009	1.119	0.263
	5	C	4.708	2.078	2.265	0.023
	6	A	-0.008	0.076	-0.101	0.919
	6	B	0.001	0.000	2.050	0.040
	6	C	17.752	0.001	23601.67	0.000
	7	A	0.176	0.028	6.275	0.000
	7	B	-0.009	0.004	-2.315	0.021
	7	C	3.101	0.465	6.666	0.000

Table 2.9: Quadratic fit to initial landing position curve (two-fixation cases) for reading ***mirrored-letter (mL)*** text: Estimates of parameters A, B and C

Session	Word Length	Parameters	Estimate	Std. Error	z value	Pr(z)
1	4	A	-0,007	0,022	-0,314	0.753
	4	B	0,078	0,009	8,332	0.000
	4	C	2,802	0,120	23,424	0.000
	5	A	0,009	0,017	0,494	0.621
	5	B	0,038	0,005	7,626	0.000
	5	C	3,593	0,172	20,842	0.000
	6	A	0,028	0,006	4,569	0.000
	6	B	0,016	0,001	12,389	0.000
	6	C	4,800	0,161	29,770	0.000
	7	A	0,015	0,016	0,943	0.346
	7	B	0,007	0,002	4,283	0.000
	7	C	6,717	0,787	8,540	0.000
2	4	A	0,002	0,004	0,446	0.656
	4	B	0,060	0,002	36,706	0.000
	4	C	3,150	0,035	89,4066	0.000
	5	A	1,316	0,331	3,974	0.000
	5	B	-0,002	0,001	-3,487	0.000
	5	C	-20,033	0,018	-1087,91	0.000
	6	A	0,002	0,019	0,095	0.924
	6	B	0,022	0,004	5,463	0.000
	6	C	4,544	0,324	14,023	0.000
	7	A	0,011	0,010	1,076	0.282
	7	B	0,010	0,002	6,450	0.000
	7	C	5,933	0,405	14,661	0.000
3	4	A	0,041	0,023	1,838	0.066
	4	B	0,054	0,010	5,436	0.000
	4	C	2,980	0,211	14,152	0.000
	5	A	0,010	0,021	0,487	0.631
	5	B	0,037	0,006	6,021	0.000
	5	C	3,654	0,227	16,110	0.000
	6	A	0,002	0,020	0,080	0.936
	6	B	0,024	0,004	5,568	0.000
	6	C	4,363	0,290	15,042	0.000
	7	A	-0,002	0,020	-0,123	0.902
	7	B	0,017	0,003	5,455	0.000
	7	C	4,990	0,329	15,169	0.000

Table 2.10: Quadratic fit to initial landing position curve (two-fixation cases) for ***reading inverted-word (iW)*** text: Estimates of parameters A, B and C

Session	Word Length	Parameters	Estimate	Std. Error	z value	Pr(z)
1	4	A	-0.460	0.116	-3.976	0.000
	4	B	0.002	0.000	5.742	0.000
	4	C	22.504	0.004	5642.92	0.000
	5	A	0.213	0.022	9.688	0.000
	5	B	-0.012	0.006	-1.884	0.060
	5	C	1.510	0.653	2.312	0.021
	6	A	0.214	0.026	8.132	0.000
	6	B	-0.018	0.005	-3.570	0.000
	6	C	2.940	0.243	12.093	0.000
	7	A	0.197	0.023	8.550	0.000
	7	B	-0.013	0.003	-3.954	0.000
	7	C	3.064	0.276	11.102	0.000
2	4	A	0.058	0.014	4.153	0.000
	4	B	0.030	0.005	5.758	0.000
	4	C	3.677	0.309	11.908	0.000
	5	A	0.006	0.054	0.115	0.909
	5	B	0.002	0.001	3.198	0.001
	5	C	11.017	0.001	11956.68	0.000
	6	A	0.042	0.116	0.361	0.718
	6	B	0.000	0.000	0.881	0.378
	6	C	24.665	0.001	41339.44	0.000
	7	A	0.167	0.025	6.785	0.000
	7	B	-0.008	0.004	-2.279	0.000
	7	C	3.522	0.439	8.024	0.000
3	4	A	0.021	0.010	2.219	0.000
	4	B	0.053	0.004	12.494	0.000
	4	C	3.185	0.106	30.049	0.000
	5	A	0.080	0.029	2.767	0.006
	5	B	0.014	0.008	1.763	0.078
	5	C	4.295	1.099	3.908	0.000
	6	A	0.057	0.114	0.502	0.616
	6	B	0.000	0.000	0.767	0.443
	6	C	25.887	0.000	51952.32	0.000
	7	A	0.165	0.022	7.515	0.000
	7	B	-0.008	0.003	-2.388	0.017
	7	C	3.685	0.426	8.654	0.000

Table 2.11: Quadratic fit to initial landing position curve (two-fixation cases) for reading ***scrambled-letter (sL)*** text: Estimates of parameters A, B and C

Session	Word Length	Parameters	Estimate	Std. Error	z value	Pr(z)
1	4	A	-0.034	0.034	-1.020	0.301
	4	B	0.087	0.014	6.051	0.000
	4	C	2.833	0.169	16.776	0.000
	5	A	0.017	0.008	2.123	0.034
	5	B	0.031	0.0024	13.118	0.000
	5	C	3.861	0.118	32.791	0.000
	6	A	0.022	0.008	2.859	0.004
	6	B	0.019	0.002	11.561	0.000
	6	C	4.563	0.155	29.519	0.000
	7	A	0.620	0.043	14.332	0.000
	7	B	0.000	7.177	-11.598	0.000
	7	C	-20.736	0.001	-19706.55	0.000
2	4	A	0.002	0.026	0.081	0.935
	4	B	0.086	0.010	8.373	0.000
	4	C	2.538	0.095	26.578	0.000
	5	A	-0.009	0.024	-0.363	0.716
	5	B	0.042	0.007	6.196	0.000
	5	C	3.580	0.210	17.015	0.000
	6	A	0.021	0.015	1.348	0.178
	6	B	0.014	0.003	4.705	0.000
	6	C	5.149	0.492	10.456	0.000
	7	A	0.618	0.055	11.303	0.000
	7	B	-0.001	0.000	-9.141	0.000
	7	C	-20.966	0.001	-17086.51	0.000
3	4	A	1.376	0.758	1.815	0.070
	4	B	-0.002	0.001	-1.553	0.121
	4	C	-22.215	0.041	-547.09	0.000
	5	A	0.025	0.009	2.778	0.005
	5	B	0.029	0.003	10.999	0.000
	5	C	3.918	0.145	27.020	0.000
	6	A	0.020	0.020	0.984	0.325
	6	B	0.015	0.004	3.698	0.000
	6	C	5.046	0.601	8.399	0.000
	7	A	-0.027	0.011	-2.442	0.015
	7	B	0.003	0.000	16.467	0.000
	7	C	10.061	0.000	49984.09	0.000

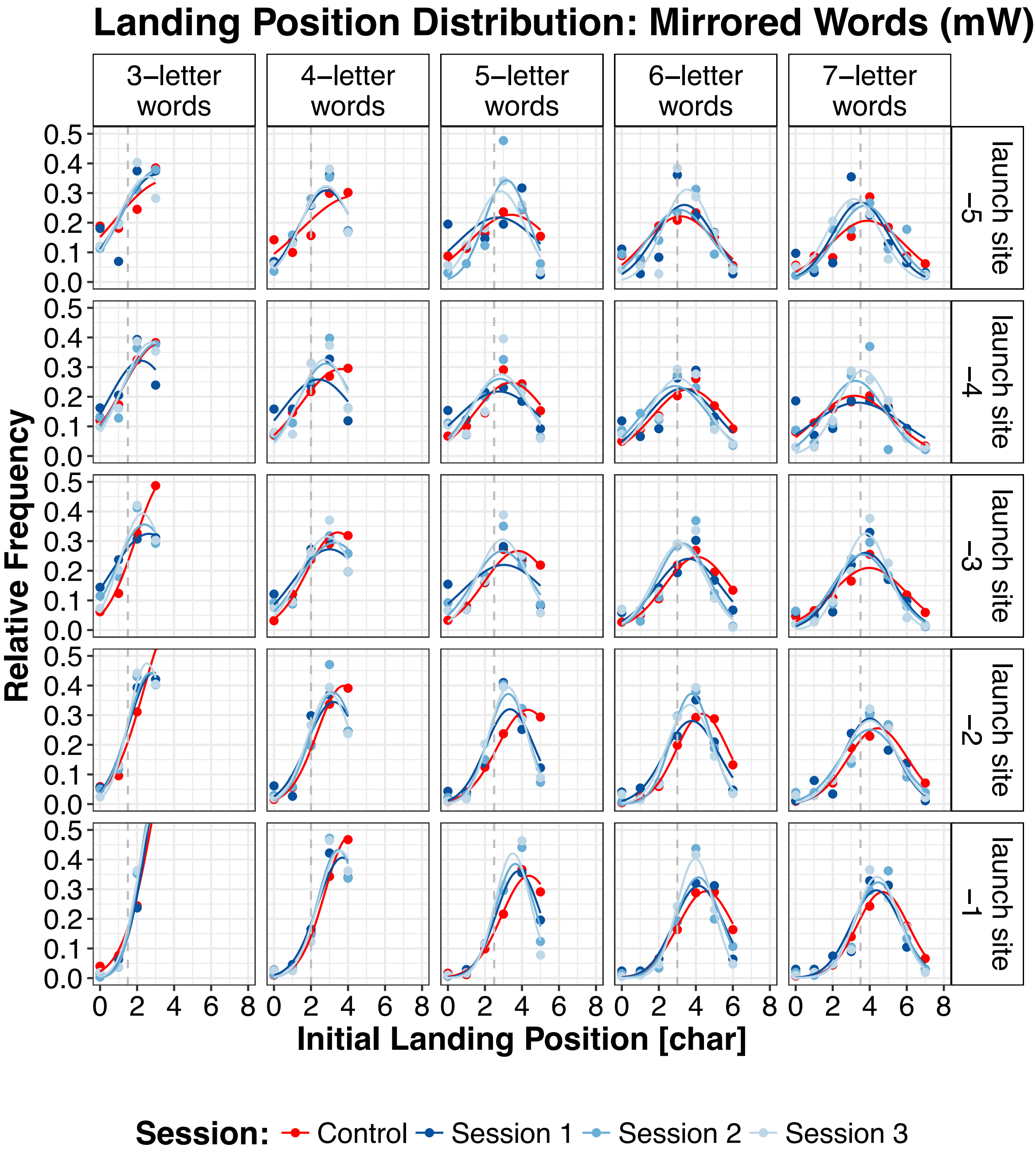

Figure 2.8: Within-word landing position distributions grouped by launch-site distance and word length for reading *mirrored-word (mW)* texts. Red lines and dots represent data from the normal reading session. Data from the first experimental session are presented in a dark blue color. The lighter blue hues represent the last two experimental sessions.

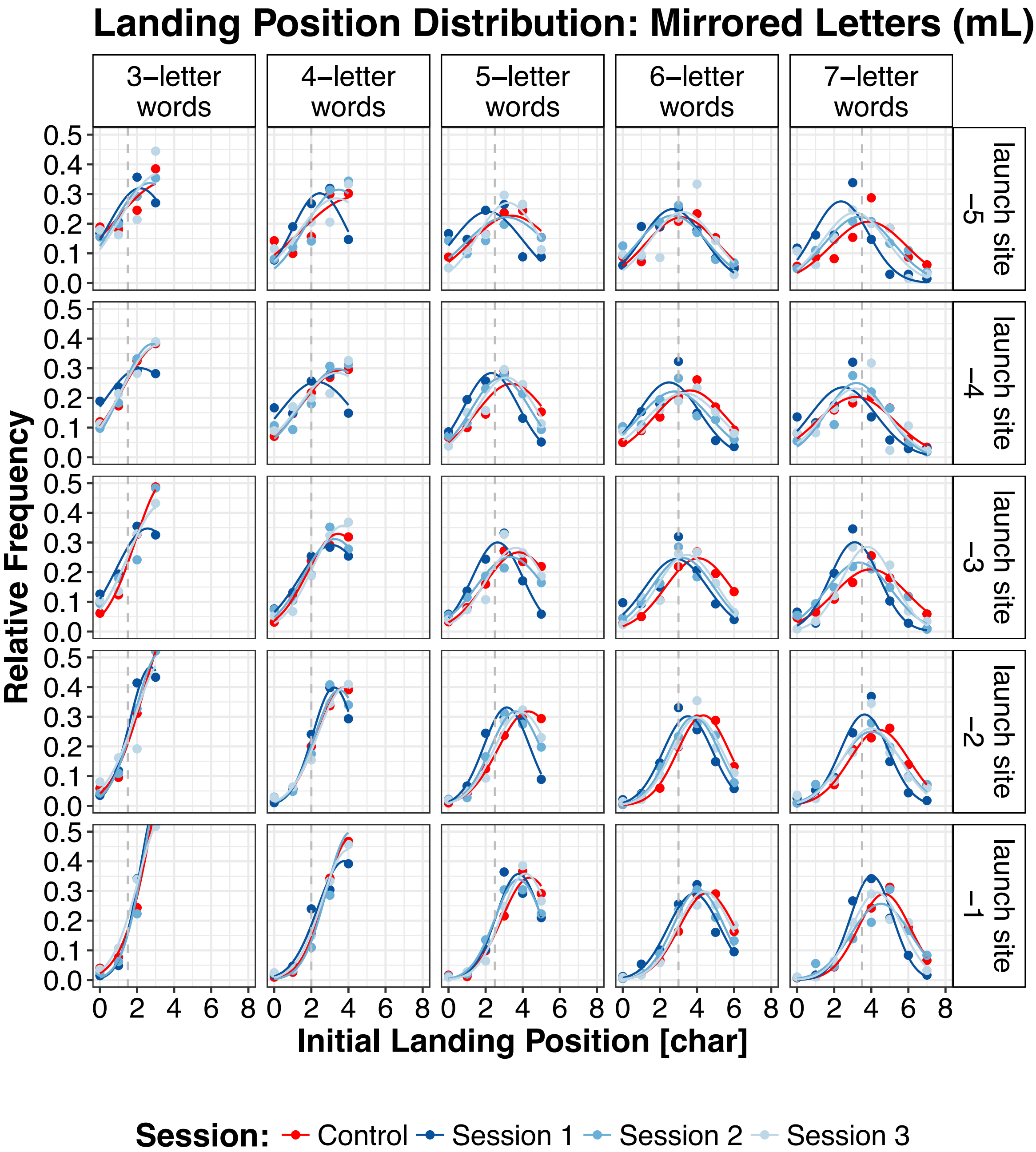

Figure 2.9: Within-word landing position distributions grouped by launch-site distance and word length for reading *mirrored-letter (mL)* texts. Red lines and dots represent data from the normal reading session. Data from the first experimental session are presented in a dark blue color. The lighter blue hues represent the last two experimental sessions.

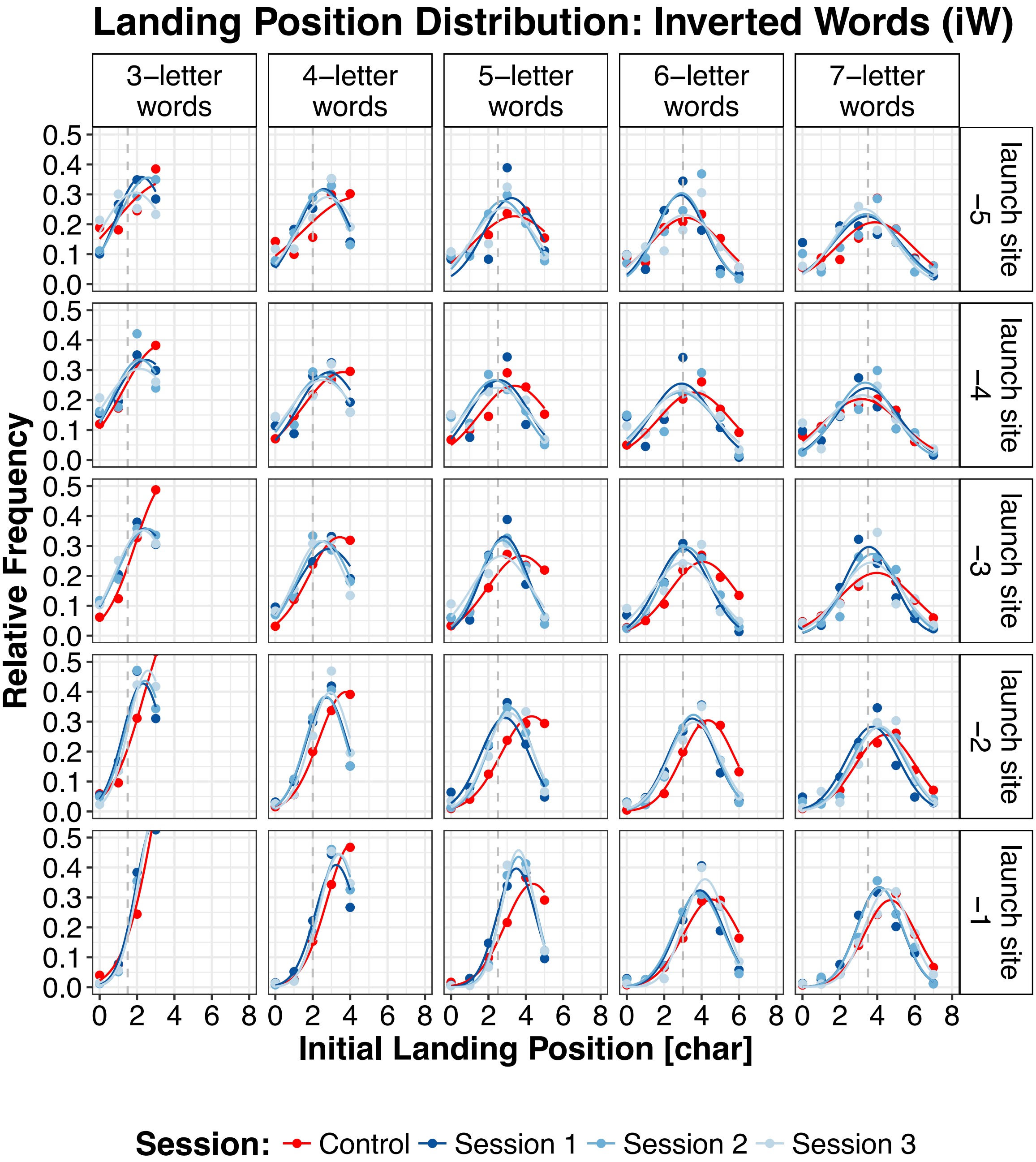

Figure 2.10: Within-word landing position distributions grouped by launch-site distance and word length for reading *inverted-word (iW)* texts. Red lines and dots represent data from the normal reading session. Data from the first experimental session are presented in a dark blue color. The lighter blue hues represent the last two experimental sessions.

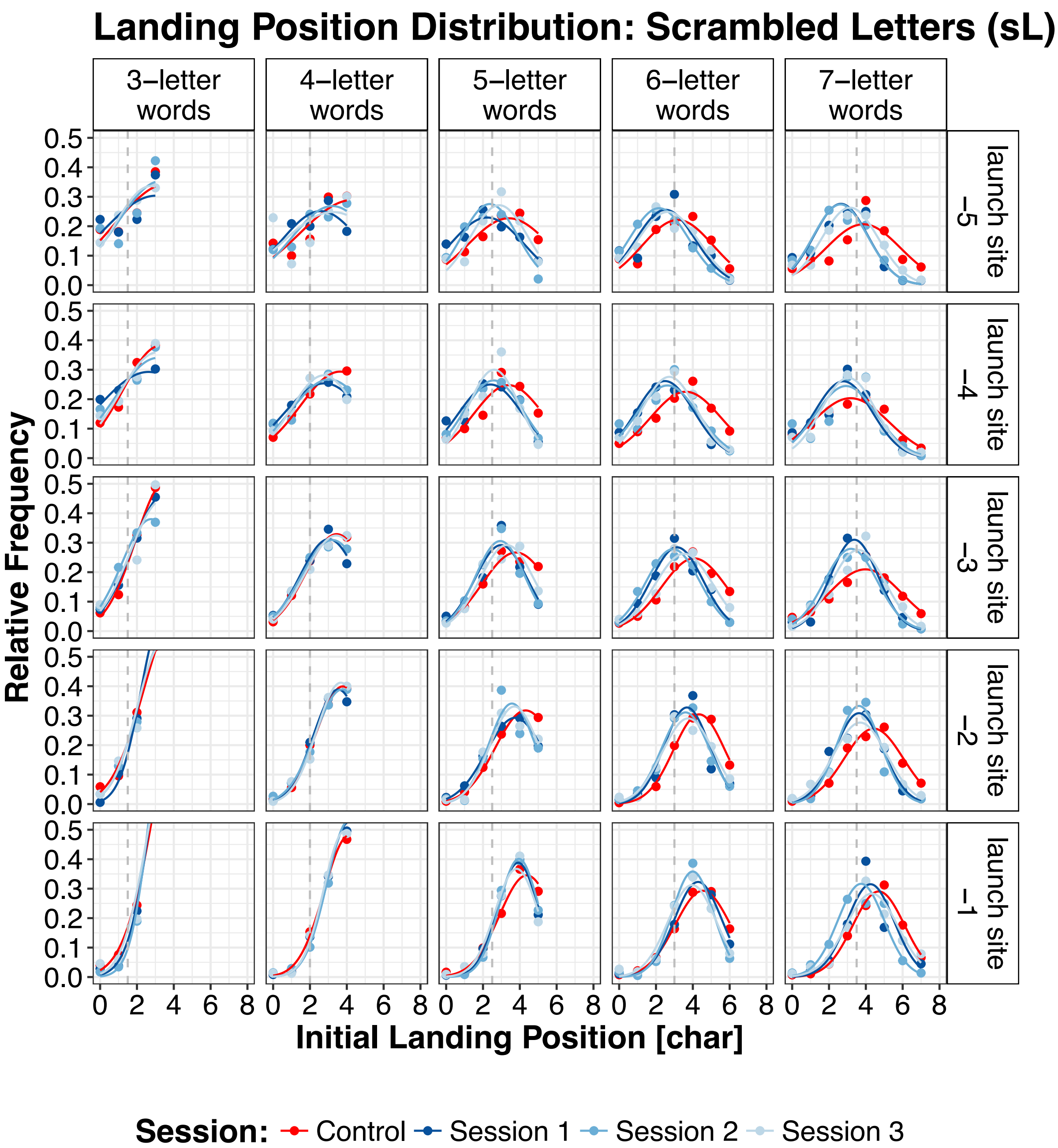

Figure 2.11: Within-word landing position distributions grouped by launch-site distance and word length for reading *scrambled-letter (sL)* texts. Red lines and dots represent data from the normal reading session. Data from the first experimental session are presented in a dark blue color. The lighter blue hues represent the last two experimental sessions.

Chapter 3

Experimental test of Bayesian saccade targeting under reversed reading direction

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Running head: Reversed reading direction

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Abstract

During reading, rapid eye movements (saccades) shift the reader's line of sight from one word to another for high-acuity visual information processing. While experimental data and theoretical models show that readers aim at word centers, the eye-movement (oculomotor) accuracy is low compared to other tasks. As a consequence, distributions of saccadic landing positions indicate large (i) random errors and (ii) systematic over- and undershoot of word centers, which additionally depend on saccade lengths (McConkie et al. *Visual Research, 28*(10), 1107–1118, 1988). Here we show that both error components can be simultaneously reduced by reading texts from right to left in German language ($N = 32$). We used our experimental data to test a Bayesian model of saccade planning. First, experimental data are consistent with the model. Second, the model makes specific predictions of the effects of the precision of prior and (sensory) likelihood. Our results suggest that it is a more precise sensory likelihood that can explain the reduction of both random and systematic error components.

3.1 Introduction

Most reading theories assume that readers aim at word centers, where visual information can be extracted optimally. The *optimal viewing position* (OVP) refers to the location within a word where refixation probablity is the lowest (O'Regan & Lévy-Schoen, 1987; Rayner, 1998; Reilly & O'Regan, 1998). However, the performance of the oculomotor system during reading, as reflected in the statistics of within-word fixation landing positions, turns out to be unexpectedly imprecise since most of the observed fixations initially do not land on word center, but slightly left of it. This off-center position was termed the *preferred viewing location* (PVL) by Rayner (1979). The saccadic landing-position errors represent an important source of variability in the reading process (Rayner, 1998). The current study is designed to investigate how the change in reading direction, i.e., German texts are read from right to left, can influence the oculomotor accuracy. We expect that the change in reading direction would interrupt readers' highly automated oculomotor control processes and, at the same time, could increase the precision of saccadic landing position. This manipulation also represents an interesting case for testing a recently developed Bayesian model of saccade planning (Engbert & Krügel, 2010), which makes explicit assumptions about the origin and the amount of random and systematic errors within the oculomotor system during reading.

Since the seminal work of McConkie and colleagues (McConkie et al., 1988), it is well known that saccades in reading inhere two different kind of errors: random and systematic components. The random error component is assumed to reflect random perceptuo-oculomotor inaccuracy in the execution of saccades leading to the observation of broad Gaussian landing-position distributions within words in reading. The systematic range-error component is interpreted as a fundamental tendency of the oculomotor system to generate saccades of an average length leading to systematic overshoots of close word centers and systematic undershoots of distal word centers. Similar effects were reported in simple saccade targeting tasks (Kapoula, 1985; Kapoula & Robinson, 1986). The systematic error can be statistically approximated by a linear landing-position function (Radach & McConkie, 1998),

$$\Delta_\mu = \lambda \cdot (L_0 - L), \tag{3.1}$$

in which the term $(L_0 - L)$ represents the deviation of saccades current launch-site distance to the center of the target word, L, from an optimal distance L_0 at which saccades during reading land on average at the word center. For L larger than L_0, negative values of Δ_μ represent the negative displacement of saccades' landing positions from the word center, i.e., a systematic undershoot. Positive values of Δ_μ, i.e., a systematic overshoot of word centers, result from launch-site distances L smaller than L_0. The slope parameter λ reflects the strength of the systematic error component. An estimated slope of $\lambda \approx 0.5$ was observed in readers of English (McConkie et al., 1988) and German (Nuthmann et al., 2005), meaning that for each letter increment of the launch-site distance L, the means of within-word landing positions shift leftward with a magnitude of half a character space. Note that in the context of the current paper, random and systematic error components are completely independent according to McConkie et al.'s (1988) model.

Based on the framework of Bayesian integration in sensorimotor control (Körding, 2007; Körding & Wolpert, 2004), Engbert & Krügel (2010) proposed a process-oriented model of Bayesian saccade planning during reading that can be used to predict the size of random and systematic oculomotor errors in reading under altered reading conditions. According to the model, saccadic errors are the result of estimating target positions, i.e., the location of word centers, based on uncertain sensory information, and learned prior knowledge. Following Bayes' rule, given a noisy sensory observation of the word center at x_0, the optimal estimate of the true position x can be calculated as the conditional posterior probability $\pi(x|x_0)$ according to

$$\pi(x|x_0) \sim q(x_0|x)p(x) \ , \tag{3.2}$$

where $p(x)$ denotes the learned probability distribution of target locations during reading (prior), i.e., the readers internal representation of the statistics of the low-level text properties such as word lengths and distances to target words. The conditional probability $q(x_0|x)$, called likelihood, reflects the sensory likelihood of the observation at position x_0 given a word center at x, i.e., uncertainty of the sensory measurement of the word centers depending on the visual input and other factors such as the allocation of attentional resources and the time available for the sensory measurements. By assuming that the prior and likelihood densities follow the Gaussian distribution function, the posterior distribution of saccadic random and systematic errors can be calculated analytically.

Random saccadic errors are reflected in the variance of the Gaussian posterior distribution, σ_P^2, which increases with increasing variance of the sensory likelihood (σ_0^2) or the prior (σ_T^2) or decreases with decreasing variance of the likelihood or prior distribution:

$$\sigma_P^2 = \frac{\sigma_T^2 \sigma_0^2}{\sigma_T^2 + \sigma_0^2} \ . \tag{3.3}$$

Furthermore, Engbert & Krügel (2010) demonstrated that the systematic error component of saccades in reading, i.e., the launch-site contingent over- and undershoot of word centers, resulted from the shift of the posterior word-center estimate towards the prior distribution: Saccades overshoot word centers near the maximum of the prior distribution and systematically undershoot more distal word centers. Most importantly for the current study, the strength of the systematic error as reflected in the parameter λ in Eq. (3.1), depends on the relative uncertainty of the prior and the sensory likelihood and can be calculated from the variances of the prior and the likelihood:

$$\lambda = \frac{\sigma_0^2}{\sigma_0^2 + \sigma_T^2} \ . \tag{3.4}$$

Interestingly, unlike the effects on the random error component, prior and likelihood variances have opposite effects on the systematic errors of saccades: Reduced observational uncertainty (signaled by a decreased likelihood variance) will result in a reduced systematic error component (i.e., decreased λ) but reduced prior variance will result in an increased systematic error component.

Here we assumed that reading against the normal reading direction would interrupt the highly automatic process of saccade planning and induce a more careful strategy of saccade control. We also assumed that the more careful saccade planning is associated with attenuated internal sensory noise (i.e., reduced likelihood uncertainty) achieved by certain mechanisms such as by increasing the time needed to plan a saccade and/or by allocating more visual-attentional resources to measure target positions. On the other hand, as the low-level properties of the text (word length statistics and distance to target words) were largely preserved in the reversed reading direction conditions, we expected that readers' prior belief on word-length statistics would remain largely unaffected.

Based on this assumptions, the Bayesian model (Engbert & Krügel, 2010) makes very strong predictions: First, according to Eq. (3.3), reduced sensory uncertainty (i.e., reduced likelihood variance σ_0^2) should lead to reduced posterior uncertainty (i.e., reduced σ_P^2), hence, reducing the random errors of saccadic landing positions within words. Second, as reduced sensory uncertainty is also related to a reduction of the systematic error component in the Bayesian model , Eq. (3.4), we expect that reading texts from right to left should also lead to reduced systematic errors, reflected by a reduced parameter λ of the linear landing positions function.

3.2 Method

3.2.1 Study design and material

Participants read an excerpt from the German version of the novel "The Adventure of the Empty House" (Doyle, 2009), which was broken into 600 lines (maximum of 85 character spaces per line). During the first eye-tracking lab session, participants read 200 lines of the excerpt in a typical direction from left to right (control condition). For the second and the third sessions, participants continued reading from the part where they left off in the previous session, but in atypical reading direction, from right to left (experimental condition). To minimize the influence of cognitive processes on within-word landing

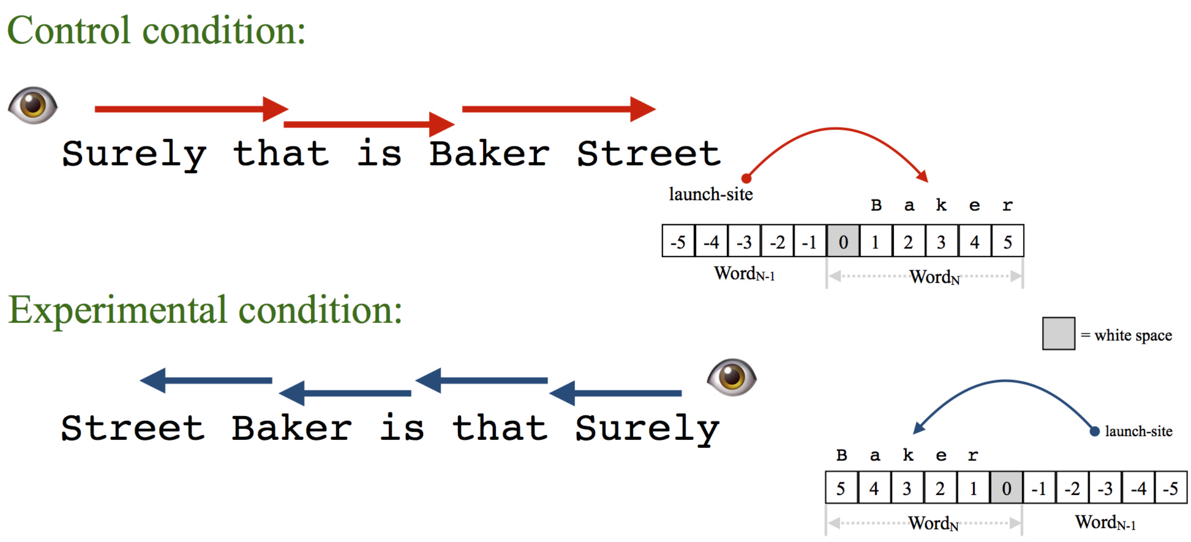

Figure 3.1: Example of experimental manipulation. Normal reading in control condition. In experimental condition, the sentence is read from right to left and incoming saccades on target $Word_N$ are calculated from the right. Letter position is coded in the global reading direction beginning with the space before the word that is denoted as letter position 0. Red and blue arrows represent saccades during reading in control and experimental conditions, respectively.

positions, individual words were presented normally, written from left to right, in all conditions with one exception: The word order in a sentence was inverted in experimental condition to match the reversed reading direction (e.g., the first word of a sentence begin on the right side of the screen; see Figure 3.1).

3.2.2 Participants and Apparatus

Analyses of our primary hypotheses are based on parameter estimates of fixations landed within 3- to 7-letter words and were launched from 1 to 5 characters away from the word beginning for each reading condition (left-to-right vs. right-to-left; all distributions contingent on word length and launch-site). Based on a large eye-movement corpus consisting of 275 adult readers (Potsdam Sentence Corpus; Kliegl et al., 2006), we analyzed the distributions of samples randomly drawn from 10, 20, and 30 participants. Using 100 independent repetitions per sample size, we estimated that 20 participants were sufficient to reproduce the estimated value of $\lambda = 0.28$ reported by Krügel & Engbert (2010) with reliability better than 0.05 character units (95% CI [0.27, 0.30]). For the current study, we exceeded the estimated sample size by testing a total of 32 participants (27 females, 5 males; age range 19 to 38 yrs). After declaring their informed consents, participants took part in three 45-min eye tracking lab sessions. They received a total of 30 euros or 3 h of course credit for their participation. Participants were all naive with respect to the purpose of the experiment and reported normal or corrected-to-normal vision. The experiment conformed to the Declaration of Helsinki.

With the head supported by a chin rest, participants read the text with a viewing distance of 70 cm in front of a 19-inch Mitsubishi Diamond Pro 2007 monitor (screen resolution 1,280×1,024 pixels, refresh rate 100 Hz). The stimuli (font: Courier, size: 18 pixels, colour: black) were presented at the vertical center line of the computer display with grey background color. Eye movements were recorded binocularly using an EyeLink 1000 System (SR Research, Osgoode/Ontario, Canada) with a sampling rate of 1000 Hz and spatial resolution better than 0.01°. Participants had to answer three questions related to the text they have just read at the end of each session. On average, two out of three questions were correctly answered on each session.

3.2.3 Data Preparation

Saccade detection and data exclusion criteria. Raw data were marked if they contained blinks. Only trials with durations of more than 1000 ms before the first detected blink were included in saccade detection procedure. Fixations and saccades information was obtained using a velocity-based algorithm developed by Engbert et al. (2003). A total of 307,908 fixations were detected. For further analysis, fixations landing on the first and last words of a sentence, as well as the first and last fixations in a trial, were excluded. Furthermore, fixations with short (less than 20 ms) and long (greater than 1000 ms) durations, fixations landing outside the text area and fixations following saccades within a character unit were also removed from the analysis. Trials containing fixations longer than 2000 ms (above 95% of the distributions) or less than three fixation points were excluded from analysis. This resulted in 166,265 valid fixations (see Section 3.8 for summary).

Landing-position distributions. All analyses on saccadic within-word landing positions are based on progressive word-to-word saccades during first-pass reading. As a first step, saccades of each session (one control, two experimental sessions) were grouped based on word length (3-7 letters) and launch-site distance (-1 to -5 characters), resulting in 25 word-length and launch-site specific data sub-samples per session. For each sub-sample, the relative frequency of saccadic landing positions on each letter within the fixated word were calculated. Next, to estimate the means and standard deviations of the distribution of landing positions, truncated Gaussian curves were fitted using Bayesian parameter inference (Kruschke, 2014) available in the package *rjags* (Plummer, 2016) in the R environment (see Section 3.8 for more details on the fitting procedure).

Fixation duration and fixation probability measures. For first-pass reading data, we computed different fixation duration measures. Single fixation duration (SFD) refers to the time spent on a word which received exactly one fixation during first-pass reading. When a word received more than one fixations in first-pass reading, the duration of the first fixation generated the first of multiple fixations duration measure (FMD). Total viewing time reflects to sum of all fixations on a word. For word-length effect analysis, fixation duration measures were calculated separately for words of length 3-11 characters. Since fixations landing on a word could come from different saccade types, we computed the word-based fixation probabilities for word-to-word saccades, word skipping, refixation and regression during the first-pass reading. Regression cases were counted for words whose saccade directions went against global reading directions, right to left for control condition and vise versa for experimental conditions, and landed on previously read words. For refixation cases, a word was refixated if it received two or more fixations consecutively, regardless the direction of the saccades.

3.3 Results

Before we present our results on saccadic landing positions, we first report the statistics of fixation duration and fixation probability measures as an overview of the global reading performances when texts were read normally and when they were read against the normal reading direction. Then, we investigate the random and systematic saccadic errors under both reading conditions.

3.3.1 Fixation duration and fixation probability

Since words were presented in their typical layout (written from left to right) in both conditions, we expected only moderate effects of changing the global reading direction (word order from right to left) on readers' fixation duration and fixation probability measures. If not otherwise mentioned, the results refer to the comparisons between the first experimental session and the control condition (normal reading).

On global level, readers' average fixation duration was 38 ms longer when texts were read from right to left compared to normal reading direction. This general prolongation in reading texts from right to left holds true across different types of fixations duration measures (single-, first-, second-of-multiple fixation durations, and total viewing time) as a function of word length. For example, the estimated means of fixation duration for words with medium (5-7 characters) length were 25-55 ms longer for all fixation types. However, as visualized in Figure 3.2, fixation duration measures as a function of word lengths in the experimental condition do not qualitatively differ from those observed in the control condition.

Moreover, we found a reduced rate of word skippings and more refixations (i.e., saccades within the same word) when texts were read from right to left. For the control condition where text are read normally from left to right, participants moved their eyes mostly from the currently fixated word to the next word (43% of the saccades). A third of the saccades skipped the word next to the currently fixated word. About 16% of observed saccades moved within a word (refixations) and 13% went backward (regressive saccades).

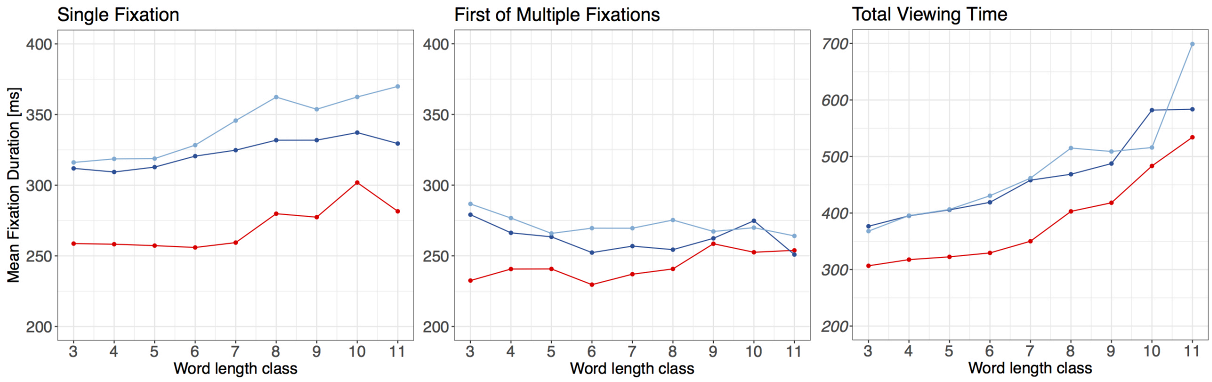

Figure 3.2: Fixation duration measures as a function of word length. *Red lines and dots* represent mean fixation durations observed in normal reading. *Dark and light blue colors* represent data observed in experimental conditions. When texts were read from right to left, readers tend to fixate longer than when texts were read normally.

Table 3.1: Regression results for the standard deviation and mean of within-word landing position distributions.

	Dependent variable:	
	Standard deviation	Mean landing position
	(1)	(2)
Launch site	-0.055^c 0.020)	0.582^c (0.033)
Right-to-left (1st)	-0.365^c (0.044)	-0.565^c (0.075)
Right-to-left (2nd)	-0.409^c (0.044)	-0.681^c (0.075)
Launch site : Right-to-left (1st)	-0.123^c (0.028)	-0.437^c (0.047)
Launch site : Right-to-left (2nd)	-0.110^c (0.028)	-0.329^c (0.047)
Constant	1.997^c (0.031)	0.959^c (0.053)
Observations	75	75
Adjusted R^2	0.777	0.864

Note: Standard errors are reported in parentheses. ^{a}p<0.1; ^{b}p<0.05; ^{c}p<0.01

When texts were read from right to left, participants generated slightly more forward word-to-word saccades (49% in the first right-to-left session and 51% in the second session). However, skipping saccades were reduced to around 17% (in both right-to-left sessions) and readers refixated words more often (20% and 22% of the time). Approximately the same proportions of regression saccades as in normal reading were observed (14% and 11% of the saccades moved backwards in the right-to-left sessions). Thus, fixation probabilities for word-to-word saccades and regressive saccades were not affected by the change in reading direction. However, the increased refixation rate and decreased skipping rate in the experimental condition may indicate that reading against normal direction requires additional effort in saccade programming processes. More detailed global summary statistics on fixation durations and fixation probabilities and the results of linear-mixed model analysis on fixation duration measures are provided in the online supplemental material.

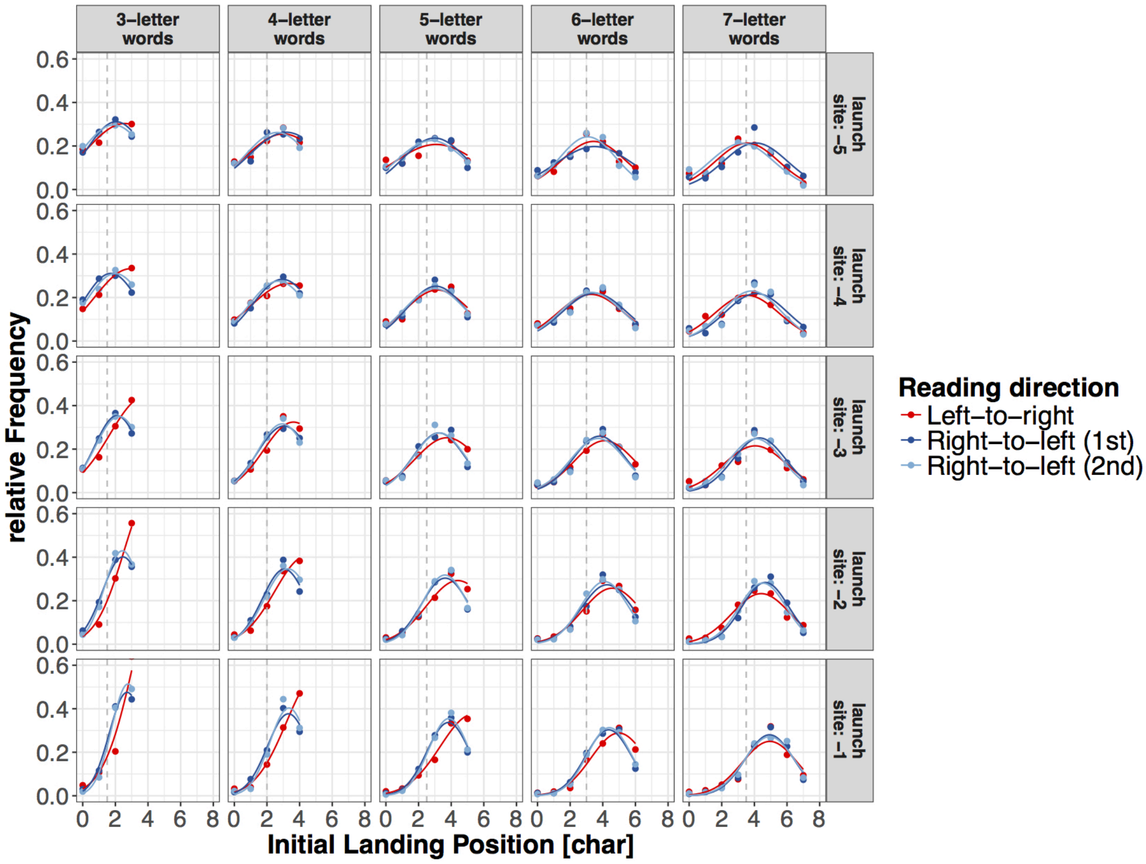

Figure 3.3: Within-word landing-position distributions of progressive word-to-word saccades based on word-length and launch-site distance. Red color represents data observed in control condition (normal left-to-right reading) and blue hues represent data observed in experimental conditions (right-to-left reading).

3.3.2 Landing position analyses

Empirical results

The current study was designed to test the assumption that reading against the normal reading direction would modulate eye movement accuracy during reading. Therefore, we analyzed both the random error component (reflected by the variance of within-word landing distributions) and the systematic error component of saccades (reflected by the strength of the launch-site contingent shift of saccades mean within-word landing positions). Figure 3.3 shows the observed distributions of saccadic landing positions for all sessions and word-length by launch-site combinations along with the obtained truncated Gaussian fits. Figure 3.3 quickly reveals that, regardless of experimental condition, landing distributions are broad (random error component) and shift within words as a function of the distance of saccades' launch sites (systematic range-error component). However, even at a first glance, Figure 3.3 suggests that distributions of saccadic landing positions in the right-to-left reading condition are narrower than the distribution in normal reading and that they seem to be more aligned to the word center. Parameter estimates (mean and SD) for each distribution are reported in the Section 3.8 online supplemental material.

For a detailed analyses of our hypotheses (reduced random errors and reduced systematic saccadic errors in right-to-left reading), separate analyses on the means and the standard deviations of the Gaussian saccadic landing distributions were conducted.

First, we looked at the effect of reading direction on the standard deviations of saccadic landing distributions within words. Figure 3.5A shows the standard deviations of the landing site distributions as a function of saccadic launch-site distances towards the centers of target words for each session; linear regression lines were fitted to the standard-deviation estimates. Saccadic landing positions are significantly narrower in the right-to-left reading condition compared to the normal left-to-right reading condition, confirming our first hypothesis that changing the reading direction reduces the random-error component in saccades. After conducting a linear regression model with (center-based) launch-site distance and session as predictor variables on landing-site standard deviation measures (see Table 3.1), we found that the difference between the standard deviations in the normal reading sesion and the first experimental session could be quantified as large as about 0.36 to approximately 0.4 character spaces on average. Furthermore, the random error component is modulated by the launch-site distance in both conditions. The modulation is stronger in the right-to-left reading condition than in the normal left-to-right reading condition. There is no difference between the first and the second experimental sessions.

Second, we analyzed the effect of reading direction on the strength of the systematic error component in saccades, i.e., the shifts of saccadic landing distributions as a function of saccadic launch-site distances towards word centers, and calculated the parameters of the linear landing position function using linear regressions. The strength of the systematic error component is reflected in the parameter λ of Eq. (3.1), i.e., the slope of the regression line. According to our predictions based on Engbert and Krügel's (2010) model of Bayesian saccade planning, we expected a reduced slope of the linear landing position function when reading from right to left. Figure 3.5B shows that our results meet the prediction: Changing the reading direction leads to a dramatically reduced systematic shift of the landing positions. Table 3.1 (right panel) shows the parameters of the regression model. In the normal left-to-right reading condition we observed a rather strong shift of mean landing positions (covariate 'Launch site': $\beta = \lambda = 0.58, p < .001$). However, when texts are read from right to left, the slope of the linear landing position functions decreases to $\lambda = 0.15$ in the first right-to-left reading session (covariate 'Launch site : Right-to-left (1st)': $\beta = -0.44, p < .001$) and to $\lambda = 0.25$ in the second right-to-left session (covariate 'Launch site : Right-to-left (2nd)': $\beta = -0.33, p < .001$).

Taken together, reversing the reading direction generates strong reductions of saccadic errors both in terms of the random fluctuations of landing positions within words, as well as in terms of the systematic over- and undershoots of word centers.

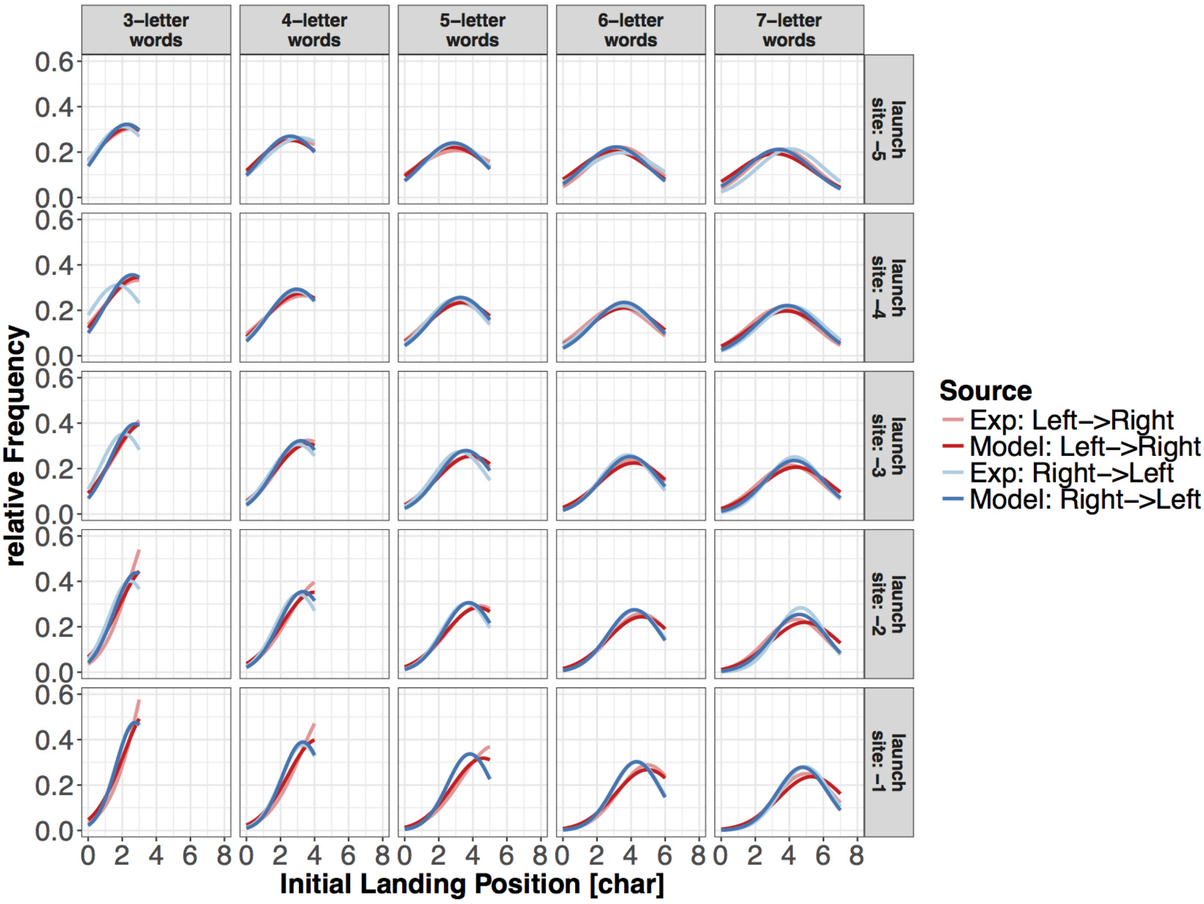

Figure 3.4: Predicted posterior estimates and observed landing position distributions. Model prediction are shown in *dark colors*, experimental observations in *light colors.Red curves* represent normal left-to-right reading condition, *blue curves* represent data and predictions from right-to-left reading.

Model simulation

In order to check the interpretations of the results, we aimed at demonstrating that a Bayesian model of saccade planning is able to simultaneously account for the observed effects on saccades' random and systematic error components during reading for both the normal left-to-right reading condition and the reversed reading condition. Following Engbert & Krügel (2010), we defined a Bayesian model based on the assumption of Gaussian prior- and likelihood probability densities (prior: $p(x) = \mathcal{N}(x; \mu_T, \sigma_T^2)$; likelihood: $q(x_0|x) = \mathcal{N}(x; x_0, \sigma_0^2)$) and also adopted the assumption that sensory observations of the word center are generally unbiased, i.e. that the maximum of the likelihood, x_0, is aligned to the center of the target word. According to our assumption that readers employ the same prior in all reading conditions, we applied the two free parameters μ_T and σ_T^2, i.e., the mean and the variance of the prior distribution, to all reading conditions in the same way. With respect to the likelihood, we assumed that the variance σ_0^2 increases linearly with increasing distance x_0 of the word center from the starting position of the saccade, i.e., $\sigma_0^2 = mx_0 + b$. For simplicity and to avoid over-fitting, we assumed that the slope parameter m is the same for both reading conditions. However, to match our central

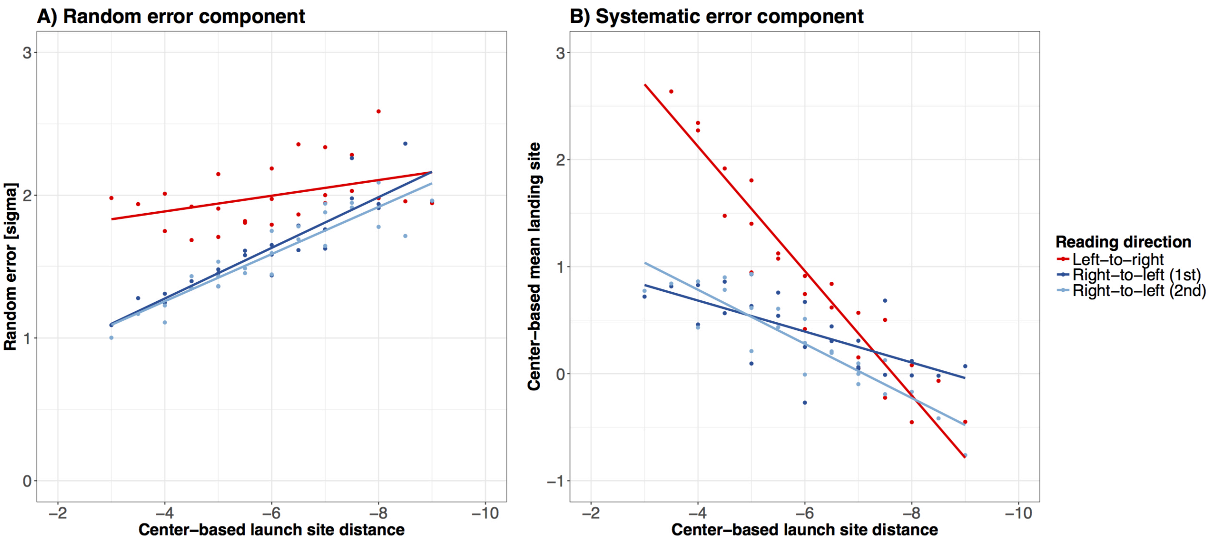

Figure 3.5: (A) Random error component: Estimated standard deviations are plotted against center-based launch-site distance to word center. (B) Mean landing positions relative to word center are plotted against launch-site distance to word center. The slope of the linear regression line represents the strength of the launch-site effect, i.e., the systematic error component. *Red color* represents data from normal left-to-right reading. *Blue hues* represent right-to-left reading.

assumption that reading against the normal reading direction led to reduced sensory uncertainty, we employed different intercept parameters for reading from left to right, b_{lr}, and reading from right to left, b_{rl}. Thus, our model included five free parameters, i.e., the mean and standard deviation of the prior (μ_T and σ_T^2), the slope parameter m and the intercept parameters b_{lr} and b_{rl} to calculate the variance of the likelihood density σ_0^2 for left-to-right reading or right-to-left reading, respectively. By using a Nelder-Mead simplex (direct-search) method (MATLAB; The MathWorks, Natick, MA), we fitted the free parameters of the Bayesian model by minimizing the sum-of-squares error (SSE) between the posterior probability estimates predicted by the model and the observed landing-position distribution from the control condition (reading from left to right) and the first session in the right-to-left reading condition. For the prior, we obtained a highly plausible mean of $\mu_T = 7.71$ and a variance of $\sigma_T^2 = 2.77$. For the likelihood, we obtained a slope parameter of $m = 0.26$, meaning that the variance of the likelihood in the model increases by 0.26 character spaces for each one-letter increment of the distance between the launch site and the word center. Most importantly, we obtained highly different intercept estimates for the calculation of the sensory uncertainty σ_0^2 in the different reading conditions. According to our hypotheses, the estimated intercept parameter for reading against the normal reading direction is more than three times smaller than the estimated intercept for the normal left-to-right reading condition: $b_{rl} = 0.45 < b_{lr} = 1.39$.

Figure 3.4 reveals a very good fit of the posterior estimates of word centers for different word length and launch-site distances as predicted by the Bayesian saccade-planning model and the landing-position distributions obtained in the reading experiment. Obviously, the model is capable in capturing both the narrower and more word-center-aligned distributions

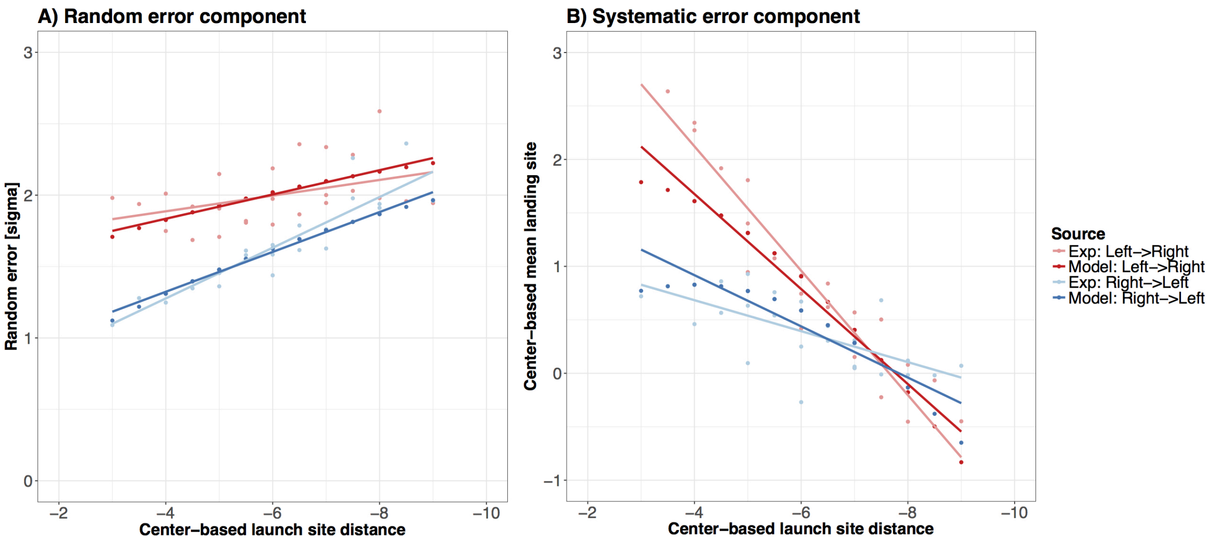

Figure 3.6: Predicted launch-site effect on systematic and random error components of within-word landing sites. (A) Random error component: Estimated standard deviations are plotted against center-based launch-site distance to word center. (B) Mean landing positions relative to word center are plotted against launch-site distance to word center. Model predictions are shown in *dark colors*, experimental observations in *light colors*. *Red* color represents normal left-to-right reading condition, *blue hues* represent data and predictions from right-to-left reading.

in the right-to-left reading conditions compared to the distributions observed in the normal left-to-right reading.

More specifically, Figure 3.6 visualizes the goodness-of-fit of the model simulations with respect to the predicted random and systematic saccadic errors when reading either under normal conditions or against the normal reading direction. First, as shown in Figure 3.6A, the model is able to reproduce the strong reduction in the random-error component of saccades as reflected in the reduced standard deviations of within-word landing position distributions. At the same time, the model also accurately predicts the reduced systematic range-error component as reflected in the decreased slope of the linear landing-position function for reading text against the normal reading direction (see Figure 3.6B).

Taken together, both the experimental data observed in the reading experiment and the numerical simulations of the Bayesian saccade planning model lend support to our assumption that reading against the typical reading direction enhances eye-movement accuracy brought about by a reduction of sensory uncertainty in the observation of the word center during saccade planning.

3.4 Discussions

In summary, our results demonstrate that reading texts in non-standard direction enhances eye movement accuracy. Saccades in reading inhere large random and systematic errors (McConkie et al., 1988), however, it is largely unknown whether these errors can be reduced. Furthermore, according to McConkie et al.'s model, there is no coupling between random and systematic error components, i.e., the model does not make the corresponding prediction that can be tested experimentally. During reading, visuo-motor and language-related processes compete for visual and attentional resources and, obviously, the observed extent of oculomotor inaccuracies in normal reading do not generally obstruct the highly efficient reading process of experienced readers. Thus, it is interesting to know whether the observed accuracy of saccades in reading reflects a fundamental accuracy limit or whether saccades in reading are only as accurate as necessary, possibly in favour of reduced resources use. Our results reveal that both saccadic error components are substantially reduced when texts are read against the normal reading direction, which clearly demonstrates that the oculomotor system is able to generate saccades with better precision and accuracy during reading. One might argue that globally shorter saccades generated under the experimental condition could be a potential explanation for the observed improved saccade targeting process. However, such an explanation is in contradiction with two points: First, the average forward saccade amplitude in the experimental condition is only one character shorter than the similar saccade amplitude observed in the control condition. These relatively shorter saccades seem to be the result from generally less skipping and/or more refixation saccades generated in the experimental condition. Second, the main analysis on the within-word landing position distributions in this study was conducted on word-to-word forward saccades only—with similar lengths for both conditions. Although there might be a different number of observations across the two conditions, effects from other saccade types can be excluded from our analysis.

More specifically, we found that readers' eye movements were less variable when reading against the normal reading direction. We estimated a drop of the standard deviation of saccadic landing distributions from about 1.6 character spaces in the standard left-to-right reading condition to approximately 0.6 character space in the right-to-left reading condition. However, this effect was modulated by the distance of the center of the target word from saccades starting positions. The effect was the largest for short distances of word centers and was marginalized for distances larger than eight letters, suggesting that the improvement of saccadic accuracy during reading might be limited to a word-center-based window of eight letters in the reading direction. Nonetheless, as it is widely accepted that in reading, word centers are computed based on information about word boundaries, i.e., the spaces before and after the words (Rayner, 1998; Krügel & Engbert, 2014), it is very likely that the effective window size for accuracy enhancements reaches 3-4 letters further into the periphery. Interestingly, that agrees well with the finding that readers obtain word-length information within a window of at least 12-15 letters from fixation position in reading direction reported by McConkie and Rayner (1975).

Even more importantly, the systematic shift of landing positions within words as a function of saccades' launch sites (the launch-site effect) was also largely reduced from a shift of slightly more than half a character for each one-letter increment of the launch-site distance in normal reading ($\lambda = 0.58$) to 0.15 and 0.25 characters in the right-to-left reading conditions. This is particularly remarkable as it has been shown that the launch-site effect during reading is very robust (McConkie et al., 1988; Nuthmann et al., 2005; Reilly & O'Regan, 1998).

Our results can be very well interpreted against the backdrop of a recently developed Bayesian saccade planning model (Engbert & Krügel, 2010) as demonstrated by the model simulations. The model replicates the simultaneous decrease in random and systematic error components and achieves an excellent goodness of fit. Our simulations demonstrate that the results are compatible with the assumption that readers in the experimental condition obtain more precise sensory information during saccade planning than those who read the texts normally from left to right. Why should this be the case? First of all, it is highly plausible that a reversal of the reading direction interrupts the otherwise highly automated saccade planning processes during reading and results in a more deliberately goal-oriented saccade control. A possible mechanism to explain the finding is a change in the distribution of covert attention which can lead to increased contrast sensitivity and noise reduction in the periphery (Carrasco, 2011). Nonetheless, obtaining more precise sensory information must come at a cost, as reflected in the increased fixation durations during the reading from right to left condition. It remains open, however, whether these increased fixation durations are directly attributable to a more precise saccade planning in general, or whether they reflect an increased lexical difficulty (e.g., due to uninformative parafoveal information) in the right-to-left reading condition or a combination of both. Thus, it is also possible that saccade control indirectly benefits from the increased reading difficulty, which results in more time to obtain the more precise sensory information before the execution of the next saccade program.

Next, it is worth considering that a simultaneous reduction of random and systematic errors is not trivial. In the range-error model proposed by McConkie et al. (1988), random and systematic saccadic errors are conceptualized as independent error components. In the Bayesian saccade planning model proposed by Engbert & Krügel (2010), however, they are inherently linked to the precision of readers' prior knowledge and the sensory likelihood. Interestingly, according to Eq. (3.4), reduced systematic errors of saccades can be the result of either increased precision of the sensory likelihood or decreased precision of the prior. On the other hand, decreased precision of the prior would inflate the random saccadic errors according to Eq. (3.3). Thus, a simultaneous decrease of both error components as observed in our reading experiment can only result from increased precision of the sensory information.

The fact that the pattern of saccadic errors in reading is typically considered as highly robust is further reflected in most computational reading models, such as the E-Z Reader model (Reichle et al., 2003), SWIFT (Engbert et al., 2005; Schad & Engbert, 2012), Glenmore (Reilly & Radach, 2006), or SERIF (McDonald et al., 2005), which incorporate the random and systematic errors of saccades based on the mathematical formulation and the numerical values reported by McConkie and colleagues (McConkie et al., 1988). However, our results show that the oculomotor system is highly adaptive and the saccadic errors can be modulated during reading to a surprisingly large extent. This emphasizes that reading models could be improved by implementing process-oriented assumptions for the saccade-planning process. The Bayesian saccade planning model (Engbert & Krügel, 2010) represents a good candidate to be integrated into these reading models. Additionally, both cognitive and oculomotor model parameters should be estimated simultaneously during model fitting.

In future studies, it would be interesting to see how different reading instructions (e.g., proofreading), which might demand for more precise saccade targeting during reading, could modulate the accuracy of eye movements, also for the standard left-to-right reading. Several studies have addressed the effects of reading instruction but with a strong focus on temporal aspects of eye-movement control (Radach et al., 2008; Kaakinen & Hyönä, 2010; Schotter et al., 2014). Radach et al. (2008) reported only minor effects of superficial versus reading-for-comprehension on saccades' global landing positions in words, but Kaakinen and Hyönä (2010) reported a left shift of landing positions under proofreading instruction. However, a comprehensive analysis of saccadic errors, both random and systematic, under different reading instructions is currently missing.

We close the discussion section by considering possible limitations of our experiment. Changing the reading direction might also affect the orthografic and lexical pre-processing of words that are next to the currently fixated word, since the relative positions of word beginnings and word endings are reversed in the right-to-left reading condition. Furthermore, the relationship between parafoveal preprocessing of words and saccades' initial landing positions within these words (the so-called *cognitive landing site effects*; Underwood & Radach, 1998) is much less clear. The literature on this issue reported controversial results, ranging from studies that argue against an effect of parafoveal preprocessing on within-word landing positions to studies reporting significant cognitive landing-site effects during reading (see Vonk et al., 2000, for a review). However, it is fair to say that the studies which claimed to find the cognitive landing-site effects reported effects that were extremely small (usually in the order of fractions of character units) compared to the effects observed in our experiment. Even more importantly, in a reading experiment where the saliency of word beginnings was manipulated (high and low initial trigram frequency), Vonk et al. (2000) found a small constant shift of landing positions by 0.3 character units to the left in words with low-frequent beginnings. The authors also analyzed saccades landing positions contingent on saccades launch-site distances but found no effect of the saliency of word beginnings on the systematic error component. Therefore, it is unclear whether the reversal of word beginnings and word endings in the reversed reading condition contributes to the observed reductions in saccadic random and systematic errors in our experiment, but we assume that such an influence would be small.

3.5 Acknowledgements

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3.6 Author contributions

R. Engbert and A. Krügel developed the study concept and the study design. Testing and data collection were performed by J. Chandra. J. Chandra and A. Krügel performed the data analysis and all authors contributed to the interpretation. J. Chandra and A. Krügel drafted the manuscript, and R. Engbert provided critical revisions. All authors approved the final version of the manuscript for submission.

3.7 Open practice statement

Neither of the experiments reported in this article was formally preregistered. Neither the data nor the materials have been made available on a permanent third-party archive; requests for the data or materials can be sent via email to the lead author at johan.chandra@uni-potsdam.de.

3.8 Appendix: Online supplemental material

Global summary statistics

Statistics of fixation durations and saccade lengths of all valid fixations were computed for a global summary analysis. Words are categorised based on their length (WLC): short ($\leq$ 4 characters), medium (5-7 characters), and long ($\geq$ 8 characters) for further statistical analysis.

Fixation durations. One way to quantify the visual information processing in reading is to examine the time spent on fixating words (fixation duration). Single fixation duration (SFD) refers to the time spent on a word which received exactly one fixation. When a word received more than one fixations in first-pass reading, the duration of the first and second fixations generated the first of multiple fixations duration (FMD) and second of multiple fixation duration (SMD). Inspection of duration distributions suggested that log-transformation is required to meet assumptions of Linear-Mixed Model. Therefore, for word-length effect analysis, the fixation duration measures were transformed into their logarithmic values.

Fixation probability. Fixation probability on a word depends on different saccade types. For first-pass reading reading data, we computed the skipping, refixation and regression probabilities. Regression cases were counted for words whose saccade directions went against reading directions, right to left for control condition and vise versa for experimental conditions. For each word that is the target of skipping saccades and refixations and/or source of regression saccades, a logical value of 1 is assigned to the word. Otherwise, a logical value of 0 was assigned.

The coefficients of the fixed effect of word-length classes and the random effect for various participants and sentences were estimated using the *lme4* package (Bates et al., 2015). Each independent variable of fixation duration and fixation probability measure is modeled as a function of word length (`WLC`) across sessions (`sess`), with a fully parameterized variance-covariance matrix for participants expressed in the term of `pID`. Furthermore, the variance for the intercept over sentence number (expressed in the terms (1|`sID`)) are taken into account. The model also allows us to examine the interaction of word-length effect between the control and experimental sessions. For instance, the log-transformed duration of the first of multiple fixations(`FMD`) is modeled as

$$\texttt{lmer}(\log(\texttt{FMD}) = \texttt{WLC} * \texttt{sess} + (1 + \texttt{WLC} + \texttt{sess}|\texttt{pID}) + (1|\texttt{sID})). \tag{3.5}$$

Likewise, refixation probability (RFP) is modeled as

$$\texttt{glmer}(\texttt{RFP} = \texttt{WLC} * \texttt{sess} + (1 + \texttt{WLC} + \texttt{sess}|\texttt{pID}) + (1|\texttt{sID})), \tag{3.6}$$

Note that the models for fixation probabilities were estimated using general function of `glmer()` due to it's ability to statistically analyse data with binary outcome. All models were estimated based on restricted maximum likelihood (REML).

Initial landing position

Within-word landing positions observed during reading are widely distributed and sometimes extend to the neighboring words. Observations of word-based landing positions in reading experiments are typically truncated at word boundaries (McConkie et al., 1988; Engbert & Nuthmann, 2008). To obtain estimations of the means and standard deviations of the landing-position distributions, truncated Gaussian curves for distributions of word-based fixation positions were fitted using Bayesian parameter inference (Kruschke, 2014) available in the package *rjags* (Plummer, 2016) in the R environment.

Only fixations from inter-word forward saccades were considered in the estimation procedure. For each session, fixation data were grouped based on word length (3-7 letters) and launch-site distance (-1 to -5 characters), resulting in three different word-length and launch-site session-specific data subsamples. For each data subset S_i, a two-dimensional posterior distribution was estimated over the parameters mean μ and standard deviation σ of the underlying Gaussian landing-position distribution conforming to

$$p(\mu, 1/\sigma^2|S_i) = \frac{p(S_i|\mu, 1/\sigma^2)p(\mu, 1/\sigma^2)}{\int\int p(S_i|\mu, 1/\sigma^2)p(\mu, 1/\sigma^2)\, \mathrm{d}\mu \mathrm{d}1/\sigma^2}\,. \tag{3.7}$$

Observations of fixation landing positions are assumed to be generated by a normal-density likelihood function $p(S_i|\mu, 1/\sigma^2)$ with mean μ and precision $\tau = 1/\sigma^2$. With $p(\mu, 1/\sigma^2)$ we specified a normally distributed prior on the mean μ with mean M and precision T and a prior on τ distributed as a gamma density distribution with shape parameter A and rate B (see Kruschke (2014)). The parameters M, T (for the prior over μ) and A,B (for the prior τ) were derived as follows: For the control condition, distributions of landing positions for each word length and launch-site distance were independently fitted by a truncated Gaussian function and the parameters of these fits were used to estimate the parameters of the empirical prior distribution. The estimated parameters from the control condition were used to estimate landing position distributions for the first experimental session and the resulting parameters were used to systematically update the prior distribution for the second experimental session.

Tables

Table 3.2: Global summary statistics.

Condition		Control	Reading Right to Left	
Session		0	1	2
Detected fixations	N	91318	116189	100401
Discarded fixation	N	46771	52141	42497
	%	51.2	44.9	42.3
Valid fixation	N	44547	64048	57903
	%	48.8	55.1	57.7
First-pass fixation	N	33331	41810	41596
	%	74.8	65.3	71.8
Forward saccades	N	14221	20525	21191
	%	42.7	49.1	51
Skipping saccades	N	9494	7188	6732
	%	28.5	12.2	16.2
Refixations	N	5456	8458	8917
	%	16.4	20.2	21.5
Regressions	N	4160	5639	4729
	%	12.5	13.5	11.4
fixation duration	mean [ms]	250	288	296
forward saccade amplitude	mean [char]	7.62	6.59	6.68
backward saccade amplitude	mean [char]	3.39	3.13	3.27

Table 3.3: Results of Linear Mixed-Effect Models for fixation duration measures.

		b	*SE*	*t value*
Single Fixation Duration (SFD)	Intercept	5.47	0.02	249.99
	WLC	0.01	0.01	**1.98**
	Session 1	0.17	0.02	11.25
	Session 2	0.20	0.01	14.06
	WLC:Session 1	-0.01	0.004	-3.06
	WLC:Session 2	0.02	0.004	4.07
First Fixation Duration (FMD)	Intercept	5.44	0.03	209.29
	WLC	0.02	0.01	**1.92**
	Session 1	0.10	0.02	5.61
	Session 2	0.11	0.02	5.40
	WLC:Session 1	-0.07	0.007	-11.10
	WLC:Session 2	-0.06	0.007	-8.76
Second Fixation Duration (SMD)	Intercept	5.32	0.03	178.05
	WLC	0.01	0.01	**1.54**
	Session 1	0.12	0.02	6.92
	Session 2	0.16	0.02	10.14
	WLC:Session 1	-0.02	0.01	-2.94
	WLC:Session 2	0.01	0.01	1.41

Note: Fixation duration values are log-transformed. WLC = word length. Non-significant values are marked in bold.

Table 3.4: Results of Linear Mixed-Effect Models for fixation probability measures.

		b	*SE*	*z value*	*Pr(>|z|)*
Skipping Probability (SKP)	Intercept	-1.58	0.11	-14.00	0.000
	WLC	-1.56	0.07	-23.50	0.000
	Session 1	0.11	0.10	1.18	**0.238**
	Session 2	-0.17	0.11	-1.53	**0.126**
	WLC:Session 1	0.44	0.02	19.81	0.000
	WLC:Session 2	0.27	0.02	11.30	0.000
Refixation Probability (RFP)	Intercept	-1.32	0.09	-14.81	0.000
	WLC	1.15	0.03	33.70	0.000
	Session 1	0.48	0.08	6.13	0.000
	Session 2	0.50	0.08	6.09	0.000
	WLC:Session 1	-0.06	0.02	-2.42	0.016
	WLC:Session 2	0.05	0.02	2.00	0.004

Note: WLC = word length centered at 5.30. Non-significant values were marked in bold.

Table 3.5: Estimation of mean (μ) and standard deviation (σ) for distributions of within-word landing position using the Bayesian fits.

Condition			Control			Right-to-left Reading					
Sessions			0			1			2		
launch site	word length	word center	μ	σ	Δ_μ	μ	σ	Δ_μ	μ	σ	Δ_μ
-5	3	2	3.07	2.34	1.07	2.55	1.76	0.55	2.40	1.94	0.40
-5	4	2.5	3.50	2.28	1.00	3.68	2.26	1.18	3.13	1.95	0.63
-5	5	3	3.58	2.59	0.58	3.48	1.94	0.48	3.29	2.09	0.29
-5	6	3.5	3.93	1.96	0.43	3.98	2.36	0.48	3.58	1.71	0.08
-5	7	4.5	4.05	1.94	0.05	4.57	1.96	0.57	3.74	1.96	-0.26
-4	3	2	3.41	2.19	1.41	2.23	1.65	0.23	2.49	1.75	0.49
-4	4	2.5	3.84	2.36	1.34	3.44	1.79	0.94	3.19	1.78	0.69
-4	5	3	3.65	2.00	0.65	3.56	1.76	0.56	3.50	1.88	0.50
-4	6	3.5	3.78	2.03	0.28	3.99	1.98	0.49	3.81	1.91	0.31
-4	7	4	4.05	1.98	0.05	4.62	1.91	0.62	4.33	1.78	0.33
-3	3	2	4.31	2.15	2.31	2.60	1.36	0.60	2.71	1.43	0.71
-3	4	2.5	4.12	1.82	1.62	3.54	1.61	1.04	3.43	1.49	0.93
-3	5	3	4.24	1.97	1.24	3.75	1.58	0.75	3.79	1.59	0.79
-3	6	3.5	4.62	1.87	1.12	4.30	1.62	0.80	4.21	1.69	0.71
-3	7	4	4.55	1.95	0.55	4.81	1.63	0.81	4.60	1.65	0.60
-2	3	2	4.77	1.75	2.77	2.96	1.25	0.96	2.93	1.11	0.93
-2	4	2.5	4.92	1.92	2.42	3.57	1.35	1.07	3.78	1.43	1.28
-2	5	3	4.90	1.91	1.90	4.13	1.45	1.13	4.11	1.36	1.11
-2	6	3.5	5.08	1.81	1.58	4.76	1.58	1.26	4.61	1.45	1.11
-2	7	4	4.92	1.79	0.92	5.17	1.44	1.17	5.01	1.45	1.01
-1	3	2	5.78	1.98	3.78	3.22	1.09	1.22	3.27	1.00	1.27
-1	4	2.5	5.64	1.94	3.14	3.82	1.28	1.32	3.84	1.17	1.34
-1	5	3	5.84	2.01	2.84	4.33	1.31	1.33	4.36	1.23	1.36
-1	6	3.5	5.48	1.69	1.98	4.86	1.40	1.36	4.90	1.35	1.40
-1	7	4	5.45	1.71	1.45	5.43	1.48	1.43	5.43	1.53	1.43

Chapter 4

On estimating within-word fixation positions: Comparison of three estimation methods

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Running head: Comparing estimation methods

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Abstract

Knowing "where" the eyes land is crucial for our understanding of oculomotor processes during reading. Within-word landing positions, however, are surprisingly noisy, making it difficult to directly infer the intended landing positions from eye movement data. To obtain estimates for the intended landing position, we analyze three different approximation methods: (1) The mean value of all observations (simple arithmetic method), (2) the peak of a truncated Gaussian distribution (i.e., based on a Gaussian fitting method), and (3) the maximum a posteriori estimator from Bayesian inference. The three methods are applied to reconstruct the known values of the mean (μ) and standard deviation (σ) of landing positions and the slope parameter (λ) of the landing-position function over the data generated using two simulation models. The mean estimation error indicates the plausibility of the methods. As a result, the Bayesian approach is most reliable, even for a small sample size (e.g., $N = 20$), in reconstructing the parameters. While the simple arithmetic method works well in estimating individual word-based fixation distributions, it shows the strongest systematic bias in estimating the slope parameter (λ) of the landing-position function that characterizes the oculomotor process during reading.

4.1 Introduction

Eye movement patterns generated during reading are complex but can be represented as a series of individual decisions about when and where to move the eyes (Radach & McConkie, 1998). For the "where" decision, saccadic eye movements are intended to shift the fovea to a specific location in words where high-acuity visual information can be processed optimally (Findlay & Gilchrist, 2003). However, inferring the intended saccades' target location is not trivial because the observed within-word landing positions delivered by eye movement data are not error-free. Therefore, it is a common practice to estimate the proxies for the intended within-word landing positions to represent the oculomotor process involved during reading (Rayner, 1979; McConkie et al., 1988). Currently, there are three approaches for the proxies for the intended landing positions during reading: (1) the mean of all observations ("Simple arithmetic mean method"), (2) the peak of truncated Gaussian distribution (i.e., based on a "Gaussian fitting method"), and (3) the maximum a posteriori estimator from Bayesian inference ("Bayesian fitting method"). This study was designed to test the reliability of the three methods commonly used for estimating the parameters (i.e., the mean (μ) and standard deviation (σ)) of landing-position distributions and the systematic oculomotor error as a function of launch-site distances, i.e., the λ parameter of the landing-position function formulated in Eq. (4.1).

Evidence from previous studies on oculomotor control during reading has led to the assumption that readers aim at word centers where visual information can be processed optimally. The *optimal viewing position (OVP)*, was first reported in experimental studies on reading isolated words (O'Regan & Lévy-Schoen, 1987; Reilly & O'Regan, 1998). A similar finding was also observed in normal reading studies (Rayner, 1998). Nonetheless, the oculomotor system does not perform well because most fixations observed during reading initially land slightly left of the word centers. The within-word fixation positions follow a normal distribution, mostly truncated at the word edges, with relatively high variance (Rayner, 1979). The fact that the word center serves as a target location for optimal processing, most saccades land on the location left off the word center. This location was termed the preferred viewing location (PVL) by Rayner & Bertera (1979). Interestingly, similar observations were reported in different languages such as German (Kliegl et al., 2004; Radach & McConkie, 1998) and Arabic (Jordan et al., 2014). Even when the linguistic information was absent such as during mindless reading, where participants were asked to read meaningless letter strings such as "zzzzz" or "xxxxx", the statistics of within-word landing positions still follow a normal distribution (Nuthmann et al., 2007; Rayner & Fischer, 1996; Vitu et al., 1995). Hence, it is assumed that oculomotor processes involved in reading are not directly linked to linguistic features of words and are highly automated.

In their influential study, McConkie et al. (1988) reported that during reading, the means of within-word landing positions varied systematically depending on the launch-site distance, i.e., the distance between the pre-saccadic fixation location and the beginning of the target word. That is, the average fixations launched from the location near the target word tend to overshoot the word center and distal saccades tend to undershoot it (systematic error component). Furthermore, McConkie et al. (1988) argued that the slightly off-centered preferred viewing location (PVL) reported by Rayner (1979) was the accumulation of distributions from different word lengths and launch-site distances.

Moreover, if the distances between the pre-saccadic fixations and the within-word fixation locations are measured relative to word centers (W_{center}), the means of within-word landing positions can be described by a linear landing-position function (see also Radach & McConkie, 1998) of the form

$$\Delta\mu = \mu - W_{center} = \lambda \cdot (L_0 - L), \tag{4.1}$$

where $\Delta\mu$ denotes the average shift of the mean landing position from the word center and L is the distance between launch site and the center of the target word. The parameter L_0 represents the optimal saccade length, i.e., the average saccades launched from this distance land on the word center.

Moreover, McConkie et al. (1988) provided the basis on how to interpret the estimated value of the slope parameter λ by presenting two extreme data patterns that could have been observed in studies on reading. First, it would have been possible to find that the eyes always land on the center of the words, with a portion of random error in achieving that target. In this extreme case, no relation between the launch site and the mean landing site (i.e., $\lambda = 0$) would have been obtained, indicating a completely center-based saccade targeting. Second, it would have been possible to find that the eyes are sent to a particular distance by generating saccades with constant average lengths all the time, i.e., there is no functional target location within words. In this case, there would have been a perfect relationship between the change in launch-site distance and the shift of the mean landing site from the word center (i.e., $\lambda = 1$), with words not influencing the saccade target selection process. However, the study by McConkie et al. (1988) reported the estimated value of $\lambda \approx 0.5$, which is between the two possible extreme values. This indicated that there exists a word-based targeting process, but at the same time, saccades generated are biased towards constant average lengths. Hence, similar to the range effect in the saccadic system reported in the study on simple saccade targeting tasks (Poulton, 1981), the launch-site effect serves as a description to represent the oculomotor error during reading.

McConkie et al. (1988) reported an estimated slope of $\lambda \approx 0.5$ for the systematic error component. In other words, for each unit increment of launch-site distance relative to the word center, the mean landing position shifts half a character towards the reading direction. A similar estimated value of $\lambda \approx 0.5$ was also reported in reading studies on other languages such as German (Nuthmann et al., 2005) and Dutch (Vonk et al., 2000). This mathematical formulation and the numerical values have been implemented in most computational reading models to incorporate the random and systematic errors of saccades. Given the fact that the estimated value of $\lambda \approx 0.5$ was reported in many studies, thus implemented in prominent computational reading models, one could assume that a similar relationship should apply to all saccade types. Note that numerous studies reporting the estimated value of $\lambda \approx 0.5$ analyzed the initial landing positions of all progressive saccades, i.e., including word-to-word forward saccades and skipping saccades.

Different saccade types may have different estimated values of λ. Krügel and Engbert (2010) analyzed the launch-site effects for skipping and word-to-word forward saccades and reported the estimated value of $\lambda = 0.66$ and $\lambda = 0.28$, respectively. Their findings imply two important aspects of the analysis of the launch-site effect. First, the robust estimated value of $\lambda \approx 0.5$ maybe because the observations analyzed were a mixture of fixations originating from both word-to-word forward and skipping saccades. Hence, the estimated values can differ from 0.5, depending on which saccade type being analyzed. Second, the estimated values can be affected by mislocated fixations, especially for saccades with extreme lengths (e.g., $L > 10$ character spaces or $L < 2$ character spaces) as they can lead to overestimation or underestimation of the parameter μ, which in turn affecting the estimation of the slope parameter λ of the landing position function. This leads to another question, what would happen if the value of λ could its extreme values (e.g., $\lambda = 1$)? Mathematically, we should expect even more observed mislocated fixations as the value of λ increases because it regulates how far the mean landing position shifts away from the center of the target word. Increasing the frequency of mislocated fixations will add difficulties in estimating the distributions of within-word landing positions. For practicality, this study focuses mainly on the mean landing position for word-to-word forward saccades.

Estimating parameters to describe the intended landing sites is not trivial. The truncation of the landing position distributions suggests that a significant proportion of saccades undershoot or overshoot their intended target words, resulting in mislocated fixations (McConkie et al., 1988). However, we do not know the intended target of saccades because the observed fixations on a particular word N originated from realized saccades. Furthermore, Nuthmann et al. (2005) proposed four important mislocated fixation cases resulting from undershoots (e.g., failed word-skipping saccades and unintended refixations) and overshoots (e.g., unintended word-skipping saccades and failed refixations). Using the self-consistent computational estimation of the likelihood of mislocated fixations observed in the normal reading, it was demonstrated that the average fraction of mislocated fixations ranges from about 10 % to more than 30 % depending on word length (Engbert & Nuthmann, 2008). Therefore, mislocated fixations were assumed to be one of the important sources of the variance of the distributions of the within-word landing position distributions (Kliegl et al., 2006).

The parameters μ and σ describing the distribution of the "intended" landing positions of saccades can be approximated using different techniques: (a) Using the mean and standard deviation of all observations and (b) Using the parameters of a Gaussian distribution that approximate the data. The curve-fitting approximation can be conducted independently for each distribution (e.g. based on a truncated Gaussian fitting method) or by assuming that all distributions are mutually informed (e.g. based on the Bayesian inference), depending on the theoretical assumptions on eye movement control during reading. The upper row of Figure 4.1 shows the relative frequency of fixation positions on a 6-letter-word and the fitted curves with parameter values estimated using the two approximation techniques. If the saccades land frequently around the target location, both techniques can deliver plausible estimations for the proxies of the intended landing location within-words. The estimated parameter values of the distribution fit the observations quite well. However, as reported in previous studies (e.g., Yan et al., 2009), readers tend to undershoot the target locations. In other words, saccades aim to land on the center of a target word N but land frequently at the beginning of that word or the preceding word $N-1$ instead (see the lower row of Figure 4.1 for an example). For the cases where the observed saccades land frequently on the word edges, the two approximation techniques can deliver different estimated values for the parameters describing the distribution of the observed within-word landing positions.

Studies focused on the eyes' landing positions during reading applied different methods to estimate the parameters that describe the distribution of fixation location within words. For example, some studies (e.g., White & Liversedge, 2004, 2006b; Deutsch & Rayner, 1999) applied the simple arithmetic values of the mean and standard deviation of the observations to describe the distributions of within-word landing positions. Other studies (e.g., Nuthmann et al., 2005; Krügel & Engbert, 2010) fitted a truncated Gaussian distribution independently for each word analyzed in the study and applied the estimated parameter values to describe the within-word landing positions. Recently, the study reported by Chandra et al. (2019) applied an approximation technique based on the Bayesian framework by assuming that the parameters describing individual distributions of fixation locations are mutually informed. By taking into the account that the a proportion of the observed fixations are indeed mislocated, estimating the parameter values to describe the intended within-word landing positions remains a challenge.

For studies whose focus is to provide a general description of "where" the eyes land during reading, the decision on how to approximate the observed distribution of within-word landing positions may be trivial. However, for studies reporting the launch-site effect as a representation of the performance of the oculomotor system during reading, the approximation method used can be crucial. The estimated value of the slope parameter λ

in the linear landing-position function formulated in Eq. (4.1) depends strongly on the estimated value of the parameter μ, which represents the "intended" landing location. As a consequence, our interpretation of the oculomotor error will be affected.

This study was set out to systematically investigate how far the three commonly used approximation methods mentioned above can deliver plausible values for the parameters that represent the intended landing sites of saccades during reading. The estimation results on word-based fixation locations play an important role in estimating the values of the slope parameter λ representing the size of the (systematic) launch-site effect. Furthermore, results from our literature research indicated that this is the first study that systematically examines the effect of the estimation methods on the launch-site effect reported in reading studies.

4.1.1 Estimation methods of within-word landing positions

The following section describes the three commonly used estimation methods tested in this study. For each word-length and launch-site specific data subset X_i, a probability density function of a normal distribution, $y_i = f(X_i) = \mathcal{N}(\mu, \sigma^2)$, was fitted to the observations. The values of the parameters μ and σ for the distribution of within-word fixation positions were estimated based using the three tested methods. As a result, we obtained 36 method-specific estimated values for the parameters describing the mean and standard deviation of the data subset. The estimated values of the parameter μ and the launch-site distance were measured relative to the word center to estimate the slope parameter λ of the regression line of the landing-position function formulated in Eq. (4.1).

Using the arithmetic mean and standard deviation of all observation (Simple arithmetic mean method)

Estimation using the arithmetic values of data is straight forward. For each distribution y_i, the mean and standard variation is calculated directly from the observed within-word fixation positions X_i where

$$\mu = \frac{1}{n} * \sum_{i=1}^{n} x_i \tag{4.2}$$

and

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n}}). \tag{4.3}$$

Using the parameters of a truncated Gaussian distribution (Gaussian fitting method)

A truncated normal distribution was fitted to the observations independently. Technically, we drew a truncated Gaussian distribution with different values of the parameters μ and

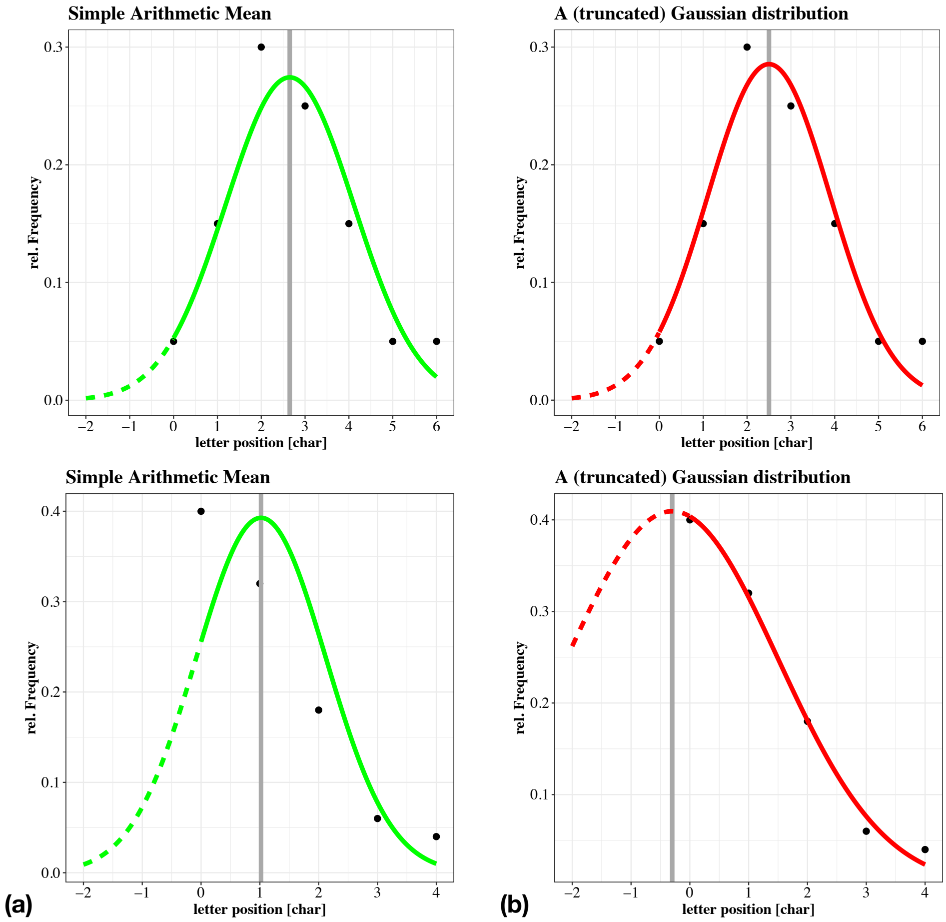

Figure 4.1: Examples of the proxies for the intended landing positions on 6-letter words (*upper row*) and on 4-letter words (*lower row*) estimated using two different methods: **(a)** Using simple arithmetic values and **(b)** using the parameters of a (truncated) Gaussian distribution to approximate the data. The green and red curves represent the approximations using the two methods, respectively. Vertical grey lines represent the "intended" landing positions within the words. For the same set of observations, different estimation methods may deliver different results for the proxy of the intended landing position. Both methods work well when most saccades land on the "intended" word (solid red and green lines). However, the simple arithmetic values are not able to represent the distribution of fixation locations within a (target) word in the case where most saccades "intended" to land on the previous word (dashed line). Letter position 0 is the space before the word, letter position -1 is the last letter of the previous word, and letter position 1 is the first letter of the word.

σ and compared it to the probability distribution of the data subset X_i. The values of the parameters μ and σ that generated a curve with the lowest discrepancy to the observed distribution were selected based on the goodness of fit criteria. The range of the tested value for the parameter μ depended on the launch-site distance and word length with a start value of $\mu_{start} = L - 1$ and an end value of $\mu_{end} = W_{center} + 2$. Moreover, the value of the parameter σ was set to range from 1 to 4 in a 0.1 step.

Using the maximum a posteriori estimator from Bayesian inference (Bayesian fitting method)

Compared to the independent truncated Gaussian fitting method, the (mutually informed) Bayesian fitting method takes all distributions analyzed into account by declaring the a priori distributions of the parameter μ and σ. Technically, for each data subset X_i, a two-dimensional posterior distribution y_i was estimated over the parameters mean μ and standard deviation σ of the underlying Gaussian landing-position distribution conforming to

$$y_i = p(\mu, 1/\sigma^2|X_i) = \frac{p(X_i|\mu, 1/\sigma^2)p(\mu, 1/\sigma^2)}{\iint p(X_i|\mu, 1/\sigma^2)p(\mu, 1/\sigma^2)\,\mathrm{d}\mu\mathrm{d}1/\sigma^2} \, . \tag{4.4}$$

Observations of fixation landing positions are assumed to be generated by a normal-density likelihood function $p(X_i|\mu, 1/\sigma^2)$ with mean μ and precision $\tau = 1/\sigma^2$. With $p(\mu, 1/\sigma^2)$ we specified a normally distributed prior on the mean μ with mean M and precision T and a prior on τ distributed as a gamma density distribution with shape parameter A and rate B (see Kruschke, 2014). The parameters M, T (for the prior over μ) and A, B (for the prior τ) were derived from the estimation results using the truncated Gaussian fitting method. The Bayesian fitting method takes information from all analyzed distributions into account by declaring the prior distribution of the parameter tested.

4.2 Simulations

One of the challenges faced by reading studies is that the observations of fixation positions within words are limited (McConkie et al., 1988). Only around 60% of the observed fixations were included in the analysis due to data filtering, e.g., blinks, first and last fixations, and second pass (e.g., Kliegl et al., 2007, 2006). Additionally, only certain word lengths were included in the analysis, e.g., 3- to 8-letter words. Moreover, one should decide whether the observations can be grouped based on the launch-site distance, which can be problematic. For instance, one might find enough observations of fixations on a 5-letter word launched 3 character spaces away from the beginning of the word, but not from 7 character spaces away. Therefore, data simulations using reading models can be a good solution to tackle the problem. Furthermore, there exists the ability to control certain parameters to test the desired effects. In this study, we are interested in the parameters that regulate the oculomotor error for word-to-word forward saccades. Specifically, the parameter λ of the landing-position function.

To find out how plausible the parameter values delivered from different estimation methods, two separate datasets were generated using two different simulation models with known values for parameters λ, μ, and σ characterizing the statistics of within-word landing positions to represent the oculomotor performance during reading. The first dataset was simulated using a simple random generation function available in R Studio.

The other dataset was generated using the standard version of SWIFT (Seelig et al., 2020) by varying the slope parameter of saccade range error for word-to-word forward fixations while keeping the default values for other parameters. Then we applied the three tested methods to estimate the mathematical values of the parameters μ, σ, and λ. For each method tested, the estimation was repeated 35 times. The following section describes how the datasets were generated.

4.2.1 Dataset I: Ideal model

The first question addressed here is how many observations are required for the estimation methods to deliver plausible proxies for the landing position distributions for each combination of launch-site distance and word length. Model I assumed that all fixations land on intended words and generate only "intended" fixations. This ideal model simulates only the linear relation between saccade launch distance and the mean landing position without taking other cognitive processes into account. Furthermore, it is assumed that all fixations observed land within target words. Technically, for each combination of launch-site distances to the beginning of word ($LSB \in \{-1, -2, -3, -4, -5, -6\}$) and word lengths ($WL \in \{3, 4, 5, 6, 7, 8\}$), different number of observations ($N \in \{20, 50, 100\}$) were sampled from a Gaussian distribution function $\mathcal{N}(\mu, \sigma^2)$. For each distribution, the parameter σ was obtained from the linear function of

$$\sigma = 1.18 + 0.03 * L, \tag{4.5}$$

as reported in (Krügel & Engbert, 2010), where the parameter L denotes the distance between the saccade launch-site to the target word center.

The parameter μ was obtained from the function

$$\mu = \frac{WL}{2} + \Delta_C + 1, \tag{4.6}$$

where the constant 1 represents the white space preceding the target word and the parameter Δ_C is the shift of the mean landing-position distribution relative to word center, resulted from the landing-position function

$$\Delta_C = -[\lambda * (L_0 - L)] \tag{4.7}$$

introduced by Radach & McConkie (1998), where the parameter L_0 represents the optimal launch-site distance, i.e., the distance where the saccades land frequently at the word center, which was set to the value of -4.66 characters as reported in (Krügel & Engbert, 2010).

Data were generated by allowing the value of the parameter λ in Eq. (4.7)to vary from

0 to 1 in 0.1 steps. For each input value of the parameter λ, the data were simulated for 35 statistical participants, resulting in eleven data subsets with a specific value of the "true slope".

4.2.2 Dataset II: Computational reading model SWIFT

The second dataset was simulated using the computational reading model SWIFT (for details, see Seelig et al., 2020), which takes various assumptions on cognitive and oculomotor processes involved in eye movement control during reading. SWIFT is able to generate "natural" reading data because it takes different saccade types and cognitive processes involved in reading into account. One of the advantages of using SWIFT is the ability to identify the mislocated fixations because the model can provide information about the realized saccades and the intended saccades. If the realized saccades land on the intended target word N, fixations observed on that particular word are labeled as "intended fixations". Otherwise, the observations are "mislocated fixations".

For this study, the numerical value of the parameter sre_fs2, equivalent to the λ in Eq. (4.1), that regulates the magnitude of the systematic shifts from the target word centers for word-to-word forward saccades was varied. All other parameters were kept constant (see Section 4.2). Similar to the simulation using the Ideal model, the values of the parameter sre_fs2 were systematically varied to change from 0 to 1 with the step of 0.1. The simulation was run until 500 fixation data points were observed on each combination of word lengths and launch sites. For each dataset generated with a specific known value of the parameter sre_fs2 (i.e., input value $\lambda = 1$), different number of observations $(N = 20, 50, 100])$ for each word-length and launch-site specific distribution were sampled. The procedure was repeated 35 times to represent 35 statistical participants. As a result, eleven data subsets specific to the input value of the "true slope" were generated.

4.3 Results

The estimation results of the three tested parameters (μ, σ, and λ) based on datasets generated from the two different models described above are visualized in Figures 4.2 and 4.3, respectively.

4.3.1 Estimation results for the dataset I: Ideal model

Estimation results from the simple arithmetic mean method

On reconstructing the parameter μ, the simple arithmetic mean method can deliver a good estimation with an error of less 1 character. Even for the data generated with a

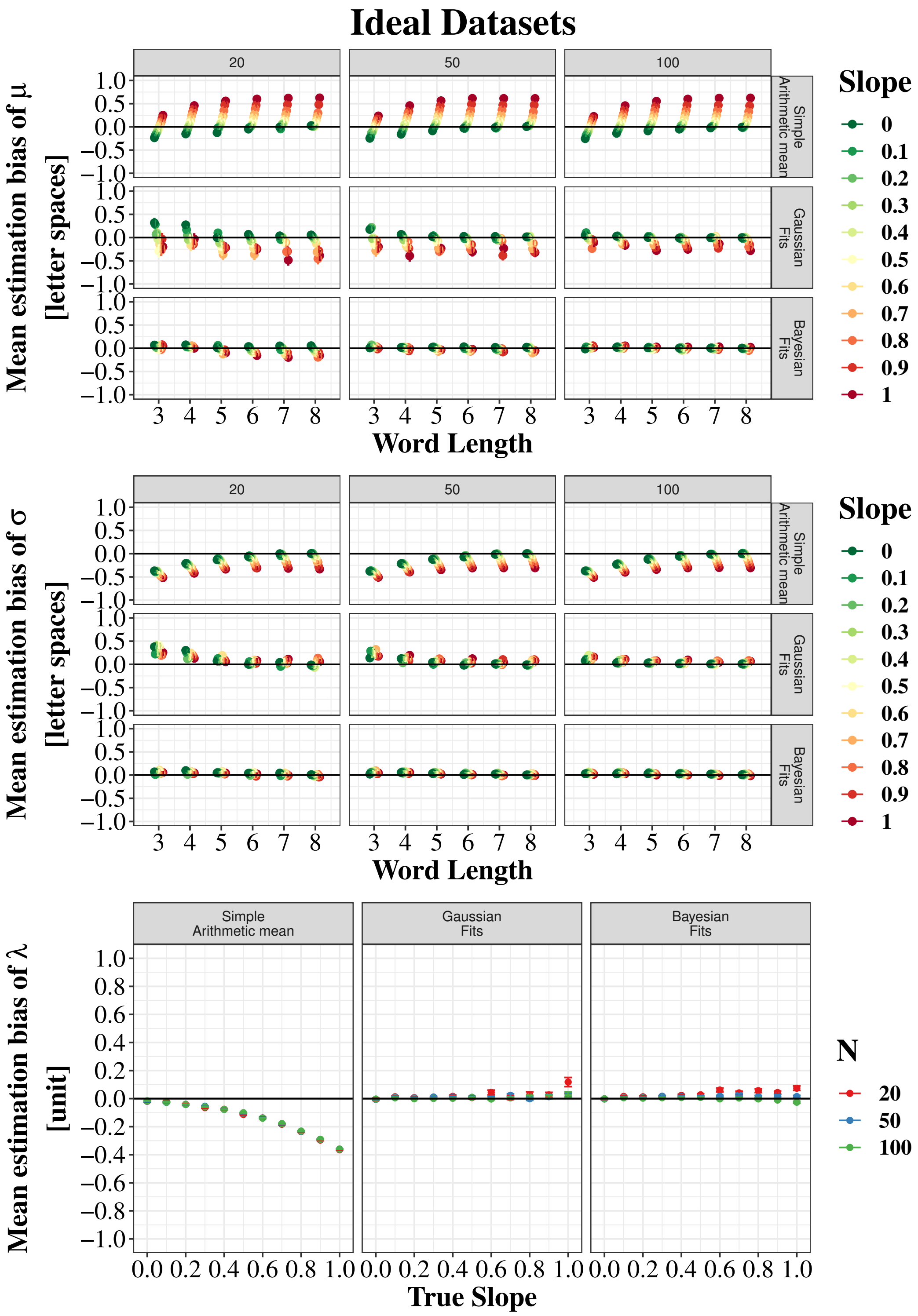

Figure 4.2: Estimation bias of parameters μ, σ, and λ from the three tested methods on the dataset generated using the Ideal Model, where saccades always land on the intended target words. The Bayesian fitting method can reconstruct the three parameters very well. However, even for the "clean" dataset, the simple arithmetic mean method shows the strongest systematic bias, especially on estimating the parameter λ.

large input value of the parameter λ, the mean estimation error of the parameter μ is still under 1 character. However, this method demonstrates a systematic dependency on the input parameter of λ and is slightly affected by word length. Furthermore, a tendency to overestimate the parameter μ is observed, especially for data generated with the input value of the parameter λ above 0.7. Increasing the number of samples does not change the trend. The simple arithmetic mean method can recover the parameter σ relatively well; the mean estimation error was under 0.5 character. Even for the data with the small sample size, the mean estimation error remains stable. Moreover, a slight word-length effect is observed. This method shows a tendency to underestimate the parameter σ, especially for landing positions within short words. For long words in data generated with a low value of the input parameter λ, the method can reconstruct the parameter value of σ. The mean estimation error of this method seems to be unaffected by the sample size.

The ability of the simple arithmetic mean method to reconstruct the parameter λ decreases as the input value of the parameter λ increases. In general, this method underestimates the parameter λ. It is understandable because mathematically, the position within a word with the highest probability to receive a fixation is constrained by the word edges. The systematic underestimation of the parameter λ can be observed when the input value of the parameter λ was set to be greater than 0.5.

Estimation results from the Gaussian fitting method

The mean absolute estimation error of parameter μ from the Gaussian fitting method is under 0.5 character. For data with a sample size of 20, the Gaussian fitting method can reconstruct the input parameter of μ with a slight overestimation on short words generated with a small value of the input parameter λ. A slight underestimation is observed for the data generated with a higher input value of the parameter λ. However, increasing the number of samples improves the ability of the method to recover the value of the parameter μ. Furthermore, there is no observable word-length effect on the mean estimation error in the results estimated using the Gaussian fitting method.

In general, the Gaussian fitting method can recover the parameter σ very well. The mean estimation errors delivered by this method approximate are almost unbiased for all input values of the parameter λ although a slight overestimation on short words can be observed. Apart from the slight bias on short words (3- and 4-letter words) for the sample size of $N = 20$, the Gaussian fitting method does not show a systematic bias on estimating the parameter σ.

As can be inferred from the estimation results on the parameter μ, the Gaussian fitting method can recover the parameter value of λ very well. A slight overestimation is observed for the data generated with the input value of the parameter λ was set to be greater than 0.5 with the sample size of $N = 20$. Nevertheless, increasing the sample size reduces the overestimation of the parameter λ.

Estimation results from the Bayesian fitting method

Compared to the other two methods, the Bayesian fitting method shows the lowest estimation error in reconstructing the parameter μ. Even on small sample size, the mean estimation error for the parameter μ is almost zero. Increasing the number of observations results in an almost perfect recovery of the known value of the parameter μ. The estimations delivered by the Bayesian fitting method is not affected by word lengths. Furthermore, no identifiable systematic bias is observed.

Likewise, the Bayesian fitting method delivers a plausible estimated value for the parameter σ; almost no systematic error is observed. The method can reconstruct the value of parameter σ precisely. The Bayesian fitting method shows the least systematic bias in recovering the value of the parameter σ. The reliability of the method improves as the sample size increases.

In general, the Bayesian fitting method generates the lowest error in estimating the parameter λ. The mean absolute estimation error of the parameter λ is under 0.1. The Bayesian fitting method slightly overestimates the parameter λ, but the overestimation can be reduced by increasing the sample size. Even for the data generated with a large input value of the parameter λ, the Bayesian fitting method is still able to deliver plausible estimation results.

4.3.2 Estimation results for the dataset II: SWIFT

Estimation results from the simple arithmetic mean method

The simple arithmetic mean method can reconstruct the parameter μ from the "natural" dataset generated by the SWIFT model. However, the mean estimation error of the parameter μ is about 2 characters for long words in the data generated with a large input value of the parameter λ. While the word-length effect is reduced for the data generated with the lowest input value of the parameter λ, the effect is obvious for the data generated with the input value of $\lambda = 1$. Since the SWIFT model can also simulate data for different saccade types, the data generated using this model contain mislocated fixations, as typically observed in experimental data. The simple arithmetic mean method is severely affected by the "added noise" in the simulation data.

The mean estimation error for the parameter σ from the simple arithmetic mean method is strongly affected by the word length. The model underestimates the standard deviation of the landing-position distributions within short words but overestimates the distributions of landing positions within long words. Although the data generated by SWIFT contain mislocated fixations that could inflate the standard deviation of the distributions, the simple arithmetic mean method is still able to reconstruct the known value of the parameter σ.

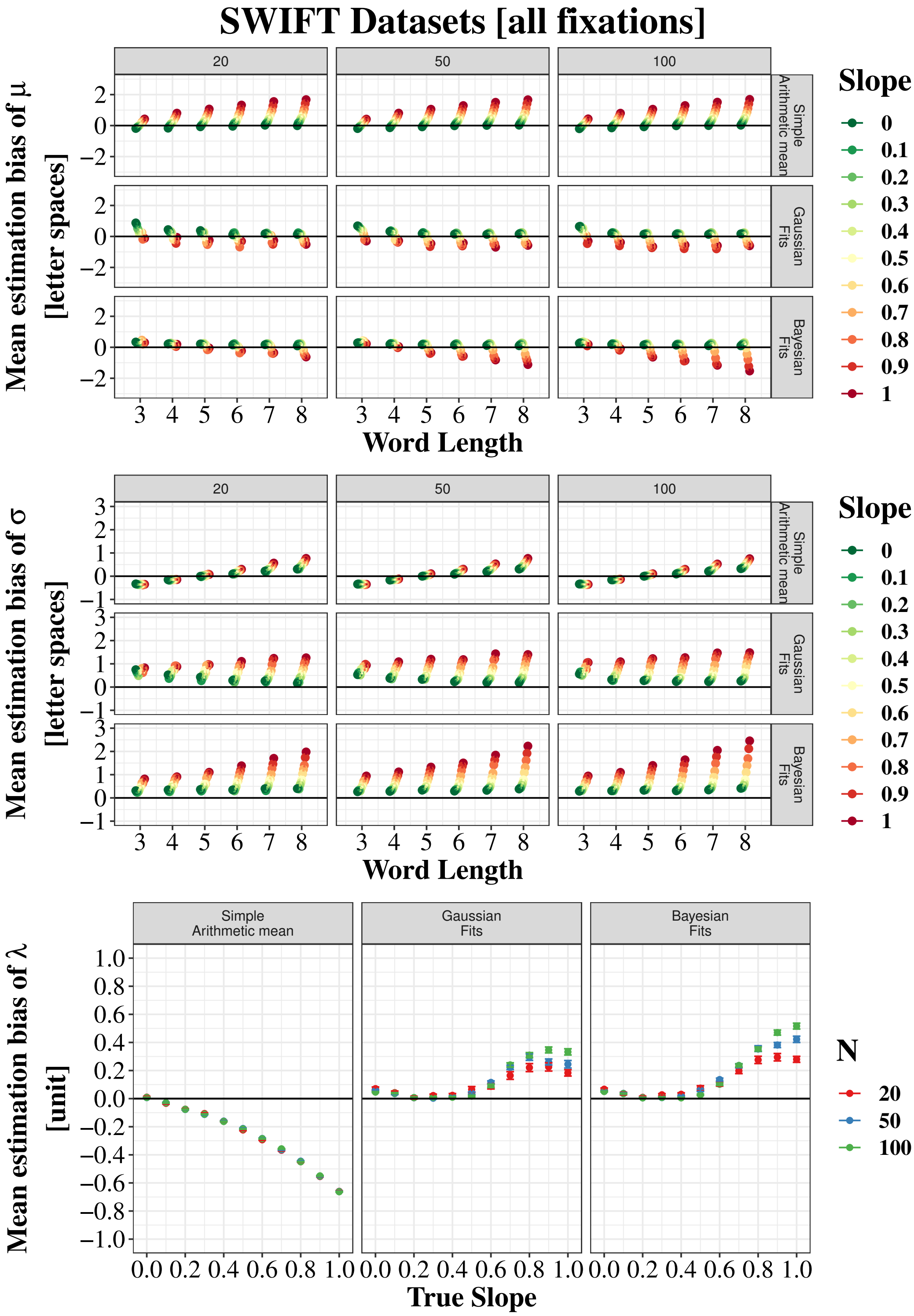

Figure 4.3: Estimation bias of the parameters μ, σ, and λ from the three methods tested on the "natural" dataset generated using SWIFT, where mislocated fixations are allowed. The simple arithmetic mean method shows the strongest systematic dependency on the input value of the parameter λ. For data generated with the input value of $\lambda > 0.6$, both Gaussian fitting and Bayesian fitting methods overestimate the parameter λ and the parameter σ. A higher input value of the parameter λ leads to an increased frequency of mislocated fixations observed, making it more difficult to reconstruct the "true" parameter values.

On estimating the "natural" data generated by SWIFT, the systematic independence between the mean estimation error and the input value of the parameter λ is stronger than the systematic bias observed in the estimation results of the "ideal" data. This systematic underestimation of the parameter λ can be observed in estimating the data generated by SWIFT, regardless the input value of the "true slope". Increasing the sample size does not improve the estimation results.

Estimation results from the Gaussian fitting method

On estimating the data generated by SWIFT, the Gaussian fitting method can still deliver good estimation results, with a slight overestimation on short words and for data generated with a small input value of the parameter λ. A slight underestimation is observed for the estimation results of the data generated with a large input value of the parameter λ. Nevertheless, the mean estimation error delivered by this method is still under 1 character. Increasing the sample size does not improve the estimation results, suggesting that the "true" distribution of the data generated by SWIFT has higher variance due to the mislocated fixations originating from different saccade types but realized as word-to-word forward saccades.

The effect of mislocated fixations is more obvious in the estimation results of the parameter σ. The Gaussian fitting method overestimates the parameter σ at about 1.5 characters for data generated with a high input value of the parameter λ (e.g., $\lambda > 0.6$. The overestimation is stronger as the sample size increases. Again, it indicates that mislocated fixations from other saccade types inflate the variance of the observations.

Mislocated fixations also affect the estimation results of the parameter λ, especially for the data generated with the input value of the parameter $\lambda < 0.6$. Compared to the estimation results using the simple arithmetic mean method, the mean estimation error of the parameter λ using the Gaussian fitting method does not show a clear systematic dependency on the input value of the parameter λ. However, the "added noise" of mislocated fixations has led to an overestimation of the parameter λ.

Estimation results from the Bayesian fitting method

The Bayesian fitting method can reconstruct the parameter μ properly on the data generated with the input value of the parameter $\lambda < 0.6$. An underestimation of the parameter μ can be observed for the data generated with a large input value of the parameter $\lambda > 0.7$, especially for data subsets within long words. The underestimation becomes more obvious as the sample increases.

As indicated in the estimation results using the Gaussian fitting method, the estimation results on the parameter σ delivered by the Bayesian fitting method shows a systematic dependency on the input value of the parameter λ. The overestimation on the parameter

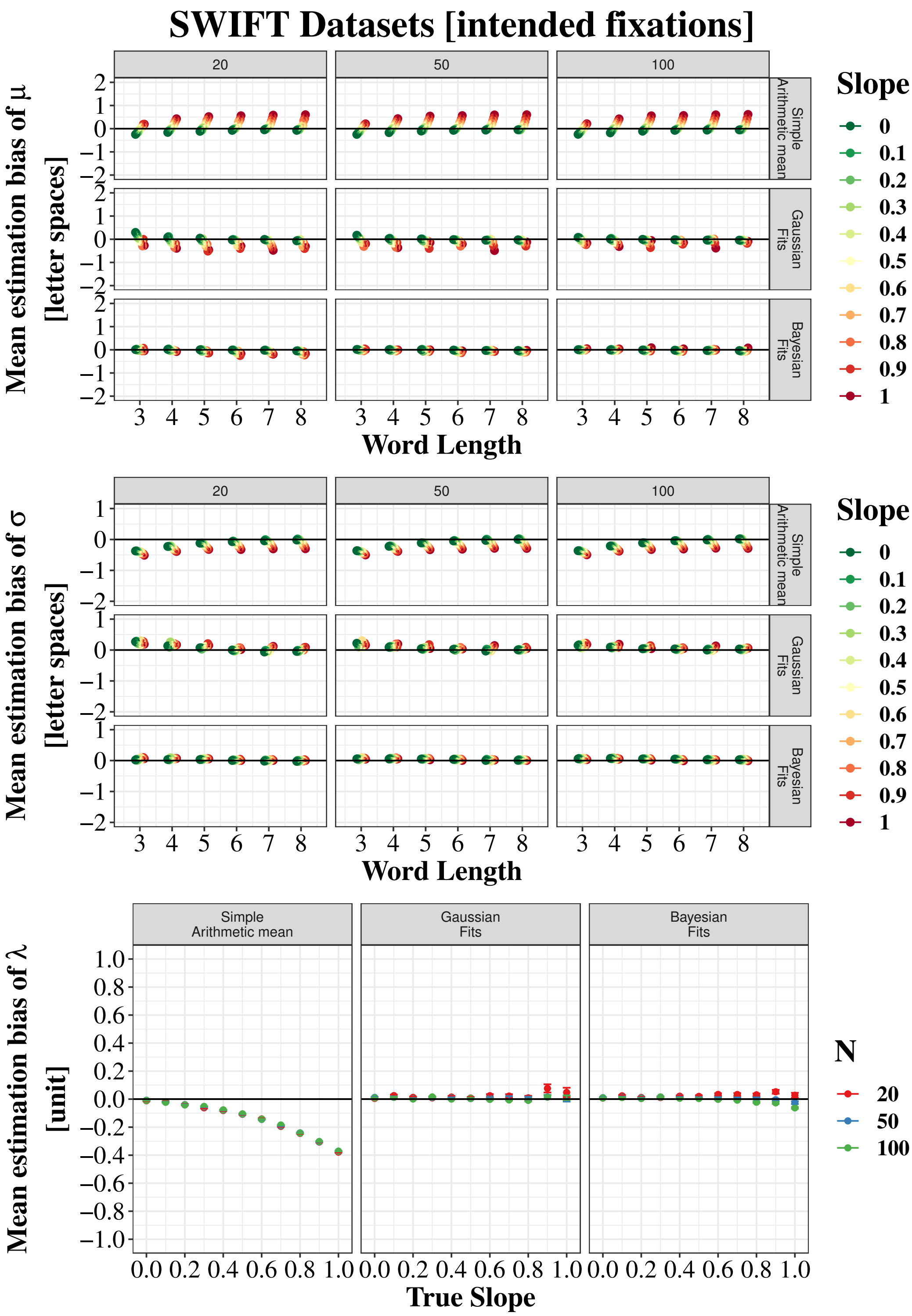

Figure 4.4: Estimation bias from three methods tested on the SWIFT dataset containing only intended fixations. When the observations do not contain mislocated fixations, all methods show results that are similar to those observed in the estimation of the dataset generated using the Ideal Model.

Table 4.1: The proportion of intended and mislocated fixations in the data generated using SWIFT.

True slope		N	%
0	intended	296872	74
	mislocated	105167	26
0.1	intended	282916	74
	mislocated	101504	26
0.2	intended	290383	73
	mislocated	104796	27
0.3	intended	298357	73
	mislocated	108413	27
0.4	intended	298754	73
	mislocated	110407	27
0.5	intended	304339	73
	mislocated	114431	27
0.6	intended	325804	72
	mislocated	124903	28
0.7	intended	351494	72
	mislocated	139210	28
0.8	intended	396335	71
	mislocated	163615	29
0.9	intended	418104	70
	mislocated	178570	30
1.0	intended	472193	69
	mislocated	211608	31

σ is larger for the data generated with a large input value of the parameter λ than for those generated with a small input value. For extreme cases, e.g., fixation positions of long words and the input value of the parameter $\lambda = 1$, the Bayesian fitting method overestimates the value of the parameter σ for about 2.5 characters.

Increasing the input value of the parameter λ allows more mislocated fixations to be observed on the word-based fixation positions. Similar to the estimation results using the Gaussian fitting method, the estimation results delivered by the Bayesian fitting method "confirm" that reconstructing the "true" value of the parameter λ is challenging due to mislocated fixations observed in the dataset. The Bayesian fitting method shows a tendency to overestimate the parameter λ for the data generated with the input value of $\lambda > 0.6$.

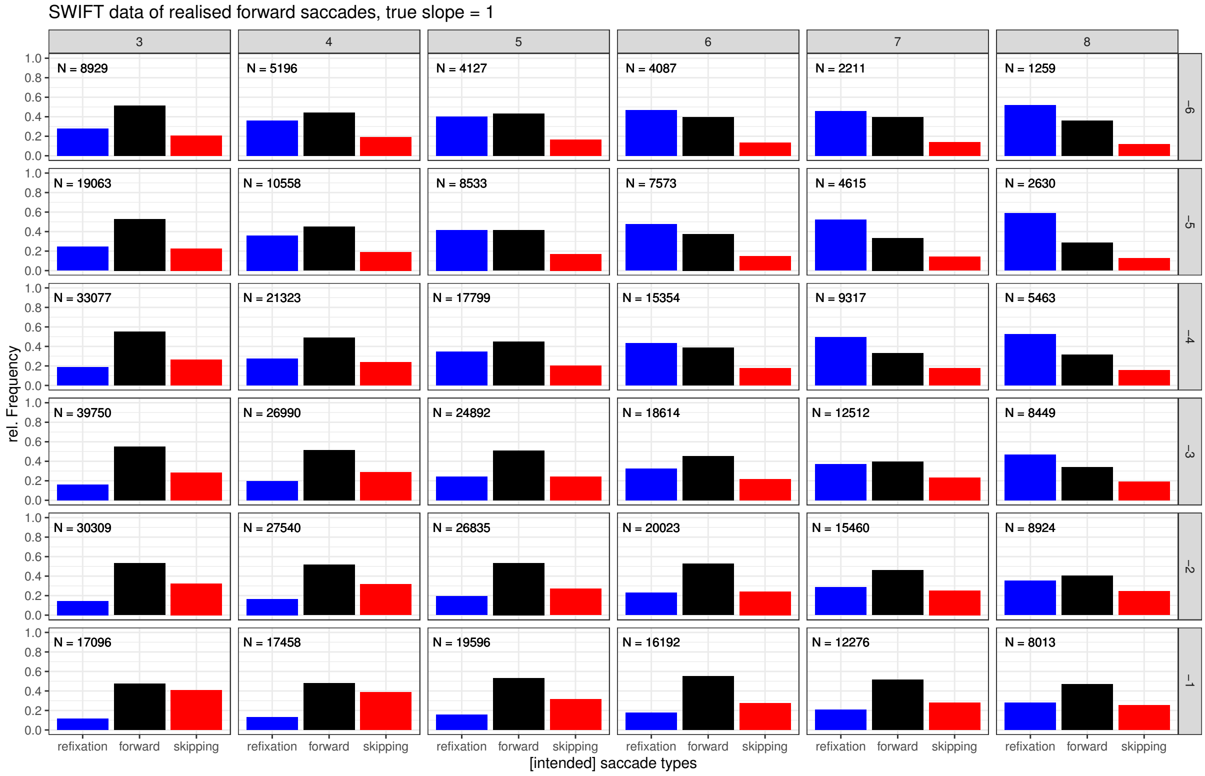

Figure 4.5: The proportion of fixations from realised word-to-word forward saccades grouped by the intended saccade types observed in the dataset generated using SWIFT with the input value of the parameter $\lambda = 1$. For short saccades (bottom row), an increased proportion of fixations originating from the intended skipping saccades but realized as word-to-word forward fixations are observed. On the other hand, for long saccades (top row), the observed fixations are dominated by fixations originally intended to re-fixate the preceding word but realized as word-to-word forward saccades.

4.3.3 Effect of mislocated fixations on estimation results

One advantage of using SWIFT to generate the simulation data is the possibility to identify the intended and mislocated fixations. It is almost impossible to directly infer the intention of saccades observed in the experimental data (but see Engbert & Nuthmann, 2008). On average, about 28% of the data generated by the SWIFT model can be identified as mislocated fixations (see Table 4.1 for a summary). The proportion of mislocated fixations in the dataset depends on the input value of the parameter λ. Data generated by a large input value of the parameter λ contain a greater proportion of mislocated fixations than the data generated by a small input value of the parameter λ. To analyze the effect of mislocated fixations on the estimation results, we filtered out the mislocated fixations from the dataset generated by the SWIFT model and repeated the estimations using the three tested methods. As shown in Figure 4.4, the estimation results from the three different methods are now similar to those observed in the estimation results on the dataset generated by the Ideal Model where no mislocated fixations are allowed.

To understand how the mislocated fixations affect the estimation results, we take a closer look at the data generated by the SWIFT model with the input parameter λ of 1. As shown in Figure 4.5, the fixations from realized word-to-word forward saccades landing

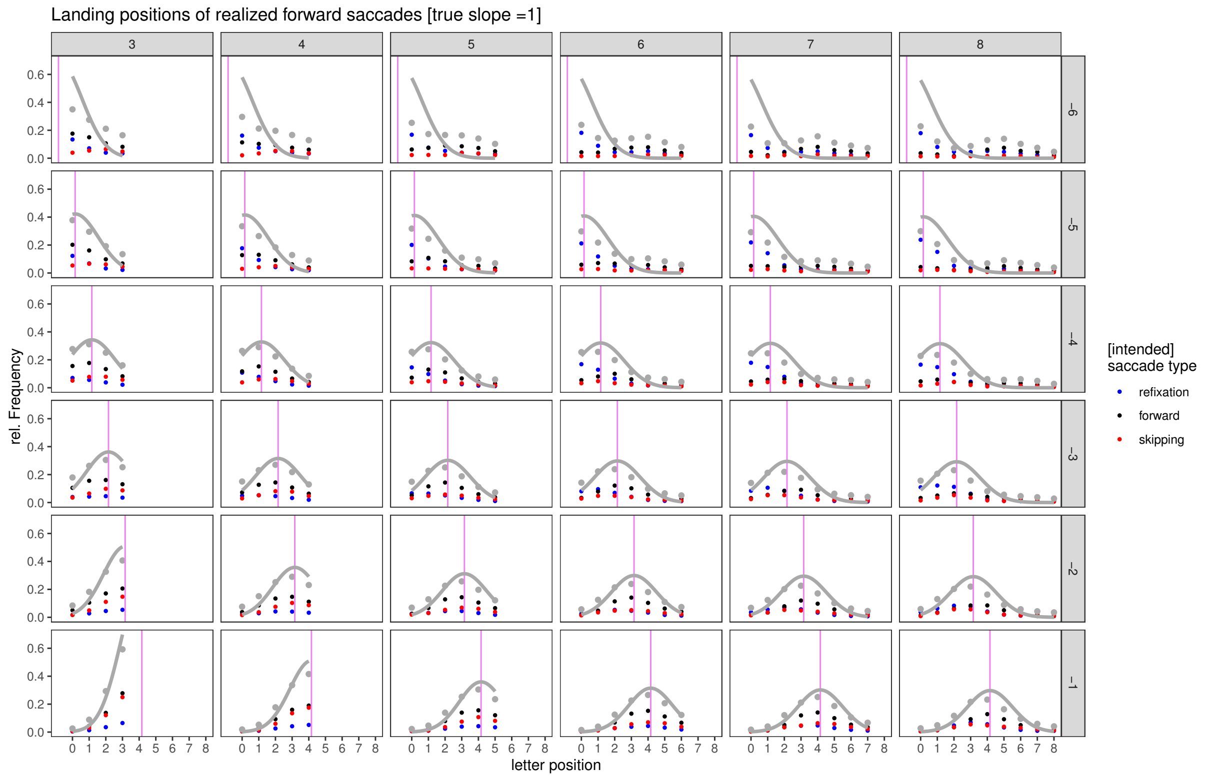

Figure 4.6: Within-word landing positions from realized word-to-word forward saccades generated using SWIFT with the input value of $\lambda = 1$. The *grey curves* represent the "true" distributions for the forward saccades from which the data were sampled. *Violet* vertical lines represent the "true" means of the distributions. *Grey dots* represent the observed fixations originating from realized word-to-word forward saccades. The *blue, black and red dots* represent the intended saccade types of the observations. Both blue and red dots are intended refixations and skipping saccades, respectively, but realized as forward saccades. Mislocated fixations add additional difficulty in estimating the variance of within-word fixation landing distribution.

on the target words originated from three different launch-site dependent, progressive saccade types: intended word-to-word forward saccades, failed skippings, and failed forward refixations. Furthermore, Figure 4.6 shows the distributions of the within-word landing positions for all target words analyzed in this study. For short saccades (e.g., fixations on 3-letter words launched 1 character away), the frequency of mislocated fixations from failed skipping saccades increases. These saccades land mostly on the end of the target word N, resulting in the rightward shift of the mean landing positions towards the next word N. On the other hand, for long saccades (e.g., fixations on 8-letter words, originating from saccades launched 6 characters away), the observed mislocated fixations originate mainly from failed refixations, i.e., saccades that aim to land on the previous word $N-1$ but land on the word N. The failed refixations land mostly on the beginning of the word N, resulting in the leftward shift of the mean landing positions. At the same time, the added "noise" from the unintended saccade types also added more variance to the observations, as reflected by the added "bumps" on the tail, especially for the fixations coming from distal saccades (e.g., the upper row of Figure4.6). Taken together, mislocated fixations lead to different **bias** on the estimation of the landing position distributions depending on the launch-site distance, which explain the overestimation of the slope parameter λ and the parameter σ.

Based on the results, the Gaussian and Bayesian fitting methods are able to recover the values of the slope parameter λ when the input value is set to be less than 0.6. Given that experimental studies in reading typically reported the value of the slope parameter that ranged from 0.2 to 0.5, the two methods are able to reduce the influence of mislocated fixations and deliver plausible results on the data generated with the input values on that range. However, mislocated fixations are problematic when the input value of the slope parameter λ is set to be greater than 0.6, i.e., the scenario where the oculomotor error is large, as both methods overestimate the value of parameter λ. In contrast, the simple arithmetic mean method constantly underestimates the parameter λ, even in the condition where the oculomotor error is moderate (e.g., $\lambda = 0.5$). For studies reporting the launch-site effect to represent the oculomotor control of eye movements during reading, using the arithmetic mean of all observations to represent the intended landing positions is not sufficient for the analysis of the launch-site effect, which serves as one of the characteristics describing the oculomotor control during reading.

4.4 Discussions

Our reading ability depends on the oculomotor performance because the oculomotor system is responsible for shifting the fovea to the regions of interests for high-acuity information processing (Findlay & Gilchrist, 2003). Therefore, knowing the location of where the eyes "intend" to land is crucial for our understanding of oculomotor processes involved during reading. However, the performance of the oculomotor system during reading, as reflected in the statistics of within-word fixation positions, turned out to be unexpectedly imprecise due to the saccadic-landing errors (Rayner, 1979, 1998), making it difficult to infer the intended landing positions from eye movement data. Within-word landing locations approximate a normal distribution, truncated on word edges (Rayner, 1979). Under this assumption, it is a common practice to adopt the parameters of μ and σ of a normal distribution to represent the intended landing location and its associated variability. Currently, there are three different approximation methods commonly used to represent the intended within-word landing positions: (1) Using the arithmetic mean value of all observations (simple arithmetic method), (2) Using the peak of truncated Gaussian distribution function (i.e., based on a Gaussian fitting method), and (3) the maximum a posteriori estimator from Bayesian inference.

Furthermore, McConkie et al. (1988) reported the launch-site effect, which provided a fundamental description of the performance of the oculomotor control of eye movements during reading. The slope parameter λ regulates the magnitude of the shift of the mean landing position towards the center of the target word, depending on the launch-site distance. The estimated value of the slope parameter λ typically reported in the reading studies is 0.5 (McConkie et al., 1988; Kliegl et al., 2004; Jordan et al., 2014). Nevertheless, it is possible to obtain an estimated value of the parameter λ that deviates from the numerical value of 0.5 (Krügel & Engbert, 2010; Vonk et al., 2000). Technically, as formulated in the landing-position function (4.1 describing the systematic launch-site effect in the oculomotor system during reading, the estimated value of the parameter *lambda* depends strongly on the estimated values of the parameter μ, that represents the mean landing position. As a result, choosing a method that can deliver plausible estimation results representing the "intended" landing position is crucial for estimating the size of the launch-site effect. This, in the end, affects how we interpret the performance of the oculomotor control of eye movements during reading.

The main focus of this study is to test the plausibility of the three methods commonly used in reading research to estimate the proxies for the intended within-words landing positions. Datasets with different sample sizes were generated using two different simulation models by varying the slope parameter of the landing-position function. The slope parameter λ regulates how far the mean landing position deviates away from the word center. A good method should be able to deliver estimation results that approximate the known values of the parameters describing the distribution of landing positions. In this case, the mean (μ) and standard deviation (σ), and the slope parameter (λ) of the landing-position function. The estimation results on the "ideal" datasets show that the Bayesian approach is the most reliable method in reconstructing the parameters, even on the data with a small sample size (e.g., $N = 20$). The Gaussian fitting method can deliver plausible results, especially on data with a larger sample size (e.g., $N = 100$). Of all the tested methods, the simple arithmetic mean method delivered the strongest systematic bias in estimating the parameter λ, regardless of the sample size, even on data without added noise (i.e., the data generated using the Ideal model).

The systematic bias of the simple arithmetic method is more obvious when it is used to estimate the "natural" datasets, which allow mislocated fixations to be observed, hence, adding noise on the observations. The systematic bias from the simple arithmetic method is even clearer and therefore should not be used to estimate the proxies for intended within-word fixation location for eye movement data. On the other hand, the Gaussian and the Bayesian fitting method are still able to estimate the mean of within-word landing locations but overestimate the standard deviation of the data distribution due to the added noise from mislocated fixations. Furthermore, for datasets generated with the input value of the slope parameter $\lambda > 0.6$, both methods overestimate the slope parameter λ. The result is understandable given that for data generated with a higher value of the slope parameter, fixations coming from inter-word forward saccades are more likely to land outside the intended target word N, reducing the number of observations of the intended fixations on that particular word. As the consequences, the observed within-word fixations on a target word N are strongly dominated by mislocated fixations originating from other launch-site dependent, progressive saccades, i.e., word skippings and refixations. As a consequence, the observed distribution of landing positions may deviate from the "true" values representing the distribution of landing positions for word-to-word forward saccades. The overestimation implies that the interpretation of eye movement data with an estimated value of slope parameter $\lambda > 0.6$ should be conducted carefully. Furthermore, the result supports the assumption that the mislocated fixations are the source of the variability observed in typical reading studies Nuthmann et al. (2005). However, assuming that most experimental data reported the value of 0.5 in different languages, one can argue that both Gaussian and Bayesian fitting methods are able to deliver plausible results on data with moderate oculomotor error (i.e, the input value of the parameter $\lambda < 0.5$).

Furthermore, the results show that estimating the statistics of within-word landing positions is not as trivial as what commonly assumed, especially when the slope parameter λ is set to be higher than 0.5. The results from this study have implications on our interpretation of reading studies applying eye-movement measures. One implication is that the commonly reported estimated value of the parameter $\lambda \approx 0.5$ is probably the upper threshold of the numerical value that can be estimated from the observations of landing positions obtained in experimental studies using eye movements. Moreover, developers of mathematical reading models should reconsider implementing processes oriented assumptions in their models, instead of direct implementation of the landing-position function to approximate the observations or the data generated. At least, a theory-driven explanation should be provided to justify the implementation of a certain numerical value in the model. The results of this study show that the input value of the slope parameter λ of the landing-position function can affect the estimation results of the statistics of the within-word landing position.

Our study shows that different methods can be used to estimate the statistics of within-word landing position to represent the oculomotor control of eye movement during reading. The Bayesian fitting and Gaussian fitting method are able to deliver plausible estimation results for the parameters that typically characterize the within-word landing positions and the launch-site effect in the range of the value that typically reported in the literature on reading research. On the other hand, the simple arithmetic method may work well in estimating the parameters for individual word-based distribution. Due to the strong systematic bias observed, using the mean value of all observations to approximate the intended landing positions is not sufficient to estimate the slope parameter of the launch-site effect. Analyzing the statistics of within-word landing position remains a challenge due to mislocated fixations. Furthermore, the development of the reading model should reconsider the implementation of oculomotor processes involved in eye movements during reading.

4.5 Appendix

Table 4.2: List of parameters used in the computational reading model SWIFT (Seelig et al., 2020) for generating the dataset II

No	Parameters	Value	No	Parameters	Value	No	Parameters	Value
1	delta0	7.23	18	refix	0.70	35	omn_sk2	0.03
2	delta1	0.00	19	kappa0	0.00	36	omn_frf1	1.18
3	asym	1.00	20	kappa1	0.00	37	omn_frf2	0.03
4	eta	0.50	21	proc	0.50	38	omn_brf1	1.18
5	alpha	50.00	22	decay	0.07	39	omn_brf2	0.03
6	beta	0.75	23	tau_l	1.20	40	omn_rg1	1.18
7	gamma	0.37	24	tau_n	0.80	41	omn_rg2	0.03
8	minact	0.00	25	tau_ex	0.20	42	sre_fs1	4.66
9	theta	0.00	26	aord	30.00	43	sre_fs2	**0 - 1***
10	msac0	1.00	27	cord	15.00	44	sre_sk1	3.00
11	msac	2.67	28	lord	12.00	45	sre_sk2	0.70
12	h	0.64	29	nord	10.00	46	sre_frf1	4.00
13	h1	0.00	30	xord	20.00	47	sre_frf2	0.30
14	ppf	0.00	31	ocshift	0.00	48	sre_brf1	4.00
15	iota	1.00	32	omn_fs1	1.18	49	sre_brf2	-0.30
16	misprob	0.90	33	omn_fs2	0.03	50	sre_rg1	0.00
17	misfac	1.50	34	omn_sk1	1.18	51	sre_rg2	0.00

*The only parameter whose value was systematically changed from 0 to 1 with 0.1 increment

Chapter 5

General discussion

Eye movement data from experimental reading studies are investigated to improve our understanding of cognitive and oculomotor processes involved in eye movement control during reading. Findings from various experimental studies using eye movement measures have led to the development of mathematical reading models as a tool to explain various phenomena observed in eye movement patterns during reading. The models are capable of making specific predictions for important experimental paradigms, as well as generating hypotheses and process-oriented interpretation on new findings from experimental studies and standard findings (e.g., from corpus studies). Most prominent computational reading models still assume that cognitive and oculomotor systems are two independent processes in controlling eye movements during reading. Recent findings (e.g., the IOVP, *inverted optimal viewing position*), however, provided evidence that the eye movement patterns observed during reading resulted from the interplay between the cognitive and oculomotor processes.

Furthermore, those reading models incorporate the mathematical value and formulation of landing position function proposed by McConkie et al. (1988) for saccade target selection. The approach proposed by McConkie et al. (1988) can statistically describe the robust launch-site effect observed under the normal reading condition. However, it does not provide further explanation of whether the oculomotor system can adapt to changes in reading condition (e.g., reading texts with reversed letter position) or can be affected by the ongoing cognitive process such as when processing load increases. Hence, certain effects on the oculomotor performance during reading can not be experimentally tested using the approach proposed by the range-error model (McConkie et al., 1988). Therefore, implementing process-oriented assumptions for the saccade-planning process could help to optimize the performance of computational reading models. A recently-proposed Bayesian model for saccade planning (Krügel & Engbert, 2014; Engbert & Krügel, 2010) serves as a good candidate to be integrated into computational reading models because it makes explicit assumptions on the source and the amount of variability observed in the statistics of within-word landing positions.

The main focus of this thesis is to acquire new information that characterizes the oculomotor performance during reading. By systematically investigating the effect of orthographic manipulation and reading direction on the statistics of within-word landing positions and the launch-site effects, new insights on the role of the oculomotor system in eye movement control during reading can be obtained. At the same time, the manipulations applied in the studies reported in this thesis serve as a means to experimentally test the predictions provided by the Bayesian model for saccade planning. Moreover, various analysis methods and inferences were applied to describe the variability of eye movement measures observed during reading.

5.1 Contribution of the results to the existing literature

The following sections summarize the main important findings from the studies reported in Chapters 2-4 and how they can contribute to our current understanding of the role of the oculomotor system in eye movement control during reading.

5.1.1 Oculomotor system is adaptive

It is possible to read texts that deviate from typical orthographical presentation, but it involves a cost, reflected in prolonged fixation durations (Rayner et al., 2006; Kowler & Anton, 1987). While the fixation durations are associated with cognitive processing difficulties, the within-word fixation positions are associated with the performance of the oculomotor process. Saccades in reading inhere large random and systematic errors, which are dependent on the launch-site distances (McConkie et al., 1988). It is unclear how far the two processes can affect each other in the eye movement control during reading. The experiments reported in Chapter 2 were set out to investigate whether ongoing cognition can overwrite the default, highly automated oculomotor control when reading condition changes.

On a global level, changing the display and positions of letters in words modulates eye-movement statistics. Similar to results reported in previous studies (e.g., Kolers & Perkins, 1975; Kowler & Anton, 1987; Rayner et al., 2006), manipulating orthographic information of text did not substantially obstruct the reading process, but resulted in increased processing difficulties, reflected by the longer average fixation duration and the shorter average saccade amplitudes. When reading conditions changed, the oculomotor system adapted to it by generating more refixations but less skipping saccades in general. Furthermore, the observed effects can be grouped based on the congruency of the reading and writing direction. Processing difficulties increased dramatically when texts were written against reading direction such as in the mirrored-word (mW) and inverted-word (iW) conditions, where the letter sequences were reversed due the mirroring or inversion. The changes in the global eye movement patterns in those conditions remained stable even after several training sessions. On the other hand, in the reading conditions where writing direction followed the typical reading direction (e.g., the mirrored-letter (mL) conditions), the global eye movement measures were qualitatively similar to those observed in the control condition and after training approximated the patterns typically observed in the normal reading condition.

On the local processing level, the adaptation of the oculomotor system can be observed in positions of fixations originating from different saccade types. When words were fixated only once (single fixation cases), the average fixation locations were near the word center, indicating an accurate saccade targeting process in both experimental and control conditions. However, the distributions of the single fixation positions in the experimental conditions contained less variance than those observed in the control condition. Interestingly, when words were fixated twice (two-fixation cases), the initial fixations landed mostly on the second half of the letter strings in conditions where letter positions were reversed. Assuming that word beginnings have a special status (Vonk et al., 2000; Johnson & Eisler, 2012; White et al., 2008), the results suggested that readers targeted the second half of the letter strings to obtain information on the initial letters of words for further processing. In other words, the oculomotor system adapted to the changes in the orthographic information. In contrast, no substantial change was observed in the two-fixation cases in the conditions where the letter position information was not manipulated.

Furthermore, modulation of manipulation types on the launch-site effect was observed for fixations originating from word-to-word forward saccades. For conditions where texts were written against reading direction, the accuracy of the saccade targeting increased, indicated by reduced launch-site effect observed. When letter position information was kept intact, an increased launch-site effect was observed, indicating that the saccade generating process was performed in a more automated manner. Interestingly, word-to-word forward saccades landed more precisely on the target words in all experimental conditions. At the same time, reading manipulated texts also resulted in longer fixation durations. It is possible that with the prolonged fixation durations under the experimental conditions, the oculomotor system gained additional time for programming more precise saccades, hence the reduced random error component of landing site distributions (McConkie et al., 1988). Alternatively, it could also be possible that the manipulations applied in the study increased the saliency of visual information of text, which facilitated the parafoveal processing, causing a better saccade programming process (Hyönä, 1995).

In general, each manipulation type applied in the study resulted in specific changes in eye movement measures, both on global and local levels, indicating specific adaptations to processing demands, temporal control of fixation duration and oculomotor control under reading texts with manipulated layouts.

5.1.2 Saccades can be accurate and precise simultaneously

Compared to simple saccade targeting tasks (Kowler & Blaser, 1995), the performance of saccades during reading is relatively imprecise. Assuming that word centers served as the functional saccade target location during reading, most (initial) fixations land slightly left of word centers with high variance (Rayner, 1979). The shift of mean landing position towards the saccadic target location depends on the saccadic launch-site distance (McConkie et al., 1988): for each increment of launch-site distance, the mean landing position shifts to the reading direction with a magnitude of 0.5 character space, hence systematic undershoots and overshoots of the word centers. On the other hand, saccades' launch-site distances also affect the random error component of fixation landing sites: short saccades contain less variance than long saccades. In the range-error model proposed by (McConkie et al., 1988), the systematic and random error components are independent: changes in saccades' accuracy do not necessarily affect their precision. Moreover, it is generally assumed that the launch-site effect during reading is rather robust. Nevertheless, the studies reported in Chapter 2 demonstrated that saccades can be accurate and precise at the same time under certain reading circumstances (e.g., when the letter sequences were reversed). However, reversing the letter sequences was also associated with increased processing difficulties, which made it difficult to infer whether the improved saccade targeting was due to the additional time available or general improvement in oculomotor performance. As a follow-up, the study reported in Chapter 3 attempted to capture the role of the oculomotor system in the improved saccade targeting and to explain the mechanism involved based on the process-oriented Bayesian saccade planning model.

As revealed by the findings reported in Chapter 2, incongruency between reading and writing direction of text resulted in the reduced systematic launch-site effect and increased precision of within-word landing positions, indicating that the performance of the oculomotor control has improved. Contrary to the general assumption that the oculomotor performance during reading was robust (Nuthmann, 2006), the study reported in Chapter 3 showed that the mean and standard deviation of within-word landing positions can be modulated by manipulating the reading direction. This finding is interesting in two ways. First, previous studies focusing on the launch-site effect on the mean landing sites reported small to no effect of experimental manipulation (Nuthmann, 2006; Vonk et al., 2000; Vitu et al., 1995). Second, the finding showed that both systematic and random error components could be modulated simultaneously, indicating that the error components of oculomotor performance are not independent.

Since the range-error model (McConkie et al., 1988) did not provide further explanation regarding the processes responsible for the oculomotor error, the findings were interpreted based on the process-oriented Bayesian saccade planning model (Engbert & Krügel, 2010; Krügel & Engbert, 2014). Through simulation with explicit assumptions that readers obtain more precise sensory information during saccade planning when texts were read from right to left, the Bayesian saccade planning model was able to generate results that approximate the experimental finding. It is plausible that reversing reading direction has interrupted the otherwise highly automated saccade planning processes and resulted in a more deliberate, goal-oriented saccade control. When reading direction changes, readers adapted by changing their covert attention, which increased in contrast sensitivity and noise reduction in the periphery (Carrasco, 2011). However, generating accurate and precise saccades comes with a cost (Kowler & Blaser, 1995), reflected in the prolonged fixation durations observed in the experimental condition.

5.1.3 Mislocated fixations: A challenge in estimating within-word landing positions

The statistics of within-word landing locations characterize the performance of the oculomotor control during reading. However, landing position distributions are relatively broad with a mean slightly left of word center and truncated at the word edges (Rayner, 1979). The variability of within-word landing positions is due to systematic and random errors in the oculomotor system (McConkie et al., 1988). As a result, these oculomotor errors produce undershoots and overshoots of word centers of intended target words depending on the distance of the pre-saccadic fixations, the launch-site effect (Radach & McConkie, 1998). Oculomotor errors also lead to saccades that land on unintended words (*mislocated fixations*), i.e., saccades that aim at target word N but land on the neighboring word $N-1$ or word $N+1$. Those mislocated fixations are partially responsible for the high variance of landing position distributions typically observed during reading (Nuthmann et al., 2005; Engbert & Nuthmann, 2008). Moreover, words are also fixated once, refixated or skipped as the consequence of the oculomotor errors.

Since the observed fixations are the result of realized saccades, but not necessarily the intended saccades, the common practice is to estimate the parameters (the mean, μ, and standard deviation, σ) of the landing position distributions as the proxy for the intended locations of saccades. It is generally accepted that the magnitude of the launch-site effect is about 0.5 character space: for one unit increment of launch-site distance, the mean landing site shifted half a character away from the center of the fixated word. However, the studies reported in Chapters 2 and 3 reported that the estimated size of the launch-site effect could deviate from the typical value of 0.5. Considering that there is no direct way to infer the intended saccade landing sites, our understanding of the oculomotor performance is strongly tied with the results of the estimation method used. Currently, there are three commonly used methods to estimate the proxies of within-word landing positions: (1)

simple arithmetic mean, (2) Gaussian fitting, and (3) Bayesian fitting methods. One way to test the reliability of an estimation method is to simulate data with certain (known) parameter values and use the method to recover the known values on data sampled from the simulation data. Note that any method used should be able to deliver plausible results despite the existence of mislocated fixations typically observed in eye movement data during reading.

Three estimation methods were compared to test their ability in reconstructing the known values of three parameters associated with the oculomotor performance during reading on the datasets generated using two different simulation models, the simple ideal model and the computational model SWIFT (Seelig et al., 2020; Engbert et al., 2005), assuming that the within-word landing sites follow a Gaussian distribution. In both models, the value of slope parameter λ of landing position function for word-to-word forward saccades was systematically varied between 0 and 1 with an increment of 0.1. Since the parameter λ regulates the size of the systematic shift of mean landing sites towards word center as the function of saccade launch-site distances, each value of the slope parameter results in various individual distributions with respective values of the mean (μ) and standard deviation (σ) for certain word length and launch-site distance. Of all the three methods tested, the Bayesian fitting method is the most reliable in reconstructing the three parameters, even for a small sample size (e.g., $N = 20$). While the simple arithmetic method performs well in reconstructing the parameters μ and σ for individual word-based fixation distributions, it shows the strongest systematic bias in reconstructing the slope parameter λ of the landing-position function that represents the oculomotor process during reading.

When the performance of the oculomotor system was at the worst (i.e., $\lambda = 1$), the frequency of saccades landing on unintended words would increase. As shown in the datasets simulated using SWIFT, where saccades intention could be identified, a large oculomotor error resulted in an increased frequency of mislocated fixations among the observed fixations. By default, for all realized saccades launched from word $N - 1$ and land on the target word N (word-to-word forward saccades), the observed fixations on the target word N should originate from saccades intended to land on that particular word and mislocated fixations, i.e., saccades intended to land on word $N + 1$ or word $N - 1$ but land on word N instead. However, increased oculomotor error for intended word-to-word forward saccades would cause the saccades to be realized as refixations, i.e., landing on word $N - 1$ or skipping saccades, i.e., landing on word $N + 1$. Hence, the frequency of fixations observed on the intended target word N was reduced. As a consequence, the observed fixations on word N would be dominated by those originating from intended skippings or refixations, which are also dependent on the launch-site distance. In the case of SWIFT data with larger values of the systematic error component, the three tested methods were used to estimate the two parameters to describe the distribution of the data, which indeed were a mixture of samples drawn from three separate distributions with different parameters. Those distributions are for three different launch-site dependent, progressive saccades: word-to-word forward saccades, skippings, and refixations. Note that only the parameters of the launch-site effect for word-to-word saccades were systematically modified in the simulations. In typical reading data, however, it is most likely that the parameters for all saccade types change simultaneously, reducing the effect of mislocated fixations on the distribution of within-word landing positions. Given that the value of $\lambda \approx 0.5$ typically reported in the literature, the Gaussian fitting method and Bayesian fitting method managed to estimate the parameters that reflect the performance of the oculomotor system and account for "noisy" data due to mislocated fixations.

5.1.4 Theoretical explanation

Reading is a complex skill that requires the coordination of visual processing under the perceptual span, attention allocation during fixations, word processing and oculomotor processes for planning and generating saccades (Pollatsek et al., 1986; Rayner, 1979; Coltheart et al., 2001; Becker & Jürgens, 1977). Since visual acuity is constrained on the fovea, saccades are generated to shift the foveal region to the target word for high-acuity information processing (Findlay & Gilchrist, 2003). Prevalent theories in reading assume that during reading the eyes aim for the centers of target words. However, the performance of the oculomotor system during reading is imprecise as saccades in reading inhere large random and systematic errors (McConkie et al., 1988). The experimental finding that signals the oculomotor performance during reading is the launch-site effect, i.e., the eyes systematically undershoot and overshoot the center of target words depending on the distance of the pre-saccadic fixations, which is very robust (McConkie et al., 1988; Nuthmann et al., 2005; Reilly & O'Regan, 1998).

In general, the results reported in Chapters 2-3 replicated the findings from previous studies (Kolers & Perkins, 1975; Kowler & Anton, 1987) that orthographically manipulated texts do not obstruct the reading process. However, reading texts with unusual presentations comes with the cognitive cost associated with processing difficulties (Rayner et al., 2006). Readers may adapt to changes in reading condition by adjusting the distribution of covert attention, which can lead to increased contrast sensitivity and noise reduction in the periphery (Carrasco, 2011). At the same time, readers reduce the perceptual span to maintain an efficient reading process. This is a plausible explanation as the perceptual span allows for detecting word length and inter-word spaces, which are important information for oculomotor targeting (Risse, 2014). A simulation study (Rabe et al., 2019) demonstrated that inverting the letter sequences is associated with a dramatically reduced perceptual span due to increased difficulties in visual processing. The oculomotor system adapted to this change by generating shorter optimal saccades, resulting in shorter average saccade length. Reading sentences with mirrored and scrambled letters is also associated with a reduced perceptual span and longer fixation time, probably due to less accurate saccade targeting. Likewise, reversing the reading direction also affected the perceptual span. Although it is generally assumed that readers obtain word-length information within a window of at least 12–15 letters from fixation position in reading direction and 3-4 letters against the reading direction (McConkie & Rayner, 1975), reversing the reading direction may cause the readers to extend their effective window size to the left, resulting in more symmetric perceptual span but still shorter than in the normal reading condition (Chung et al., 2017). This explanation can be experimentally tested by applying the moving window paradigm (Starr & Rayner, 2001).

Modulation of the launch-site effect on the fixation landing sites was observed. For conditions where letter sequences were incongruent with the reading direction, a reduced launch-site effect on the systematic error component was observed, indicating that saccades generated were more accurate than in the normal reading condition. However, in conditions where letter position information was kept intact, the systematic oculomotor error increased, indicating a less accurate saccade targeting. Since the range-error model did not predict that the oculomotor error can be modulated, the findings can be interpreted based on the process-oriented Bayesian model for saccade targeting (Engbert & Krügel, 2010; Krügel & Engbert, 2014). According to this model, the mean and variance of the fixation landing sites are linked together and depend on the relative (un)certainty of prior knowledge about the distribution of target locations based on various distances and the observational uncertainty of target location during reading. Furthermore, the magnitude of the systematic shift towards word centers, the slope parameter λ, also depends on the uncertainty of prior distribution and sensory likelihood. The estimated value of $\lambda \approx 0.5$ typically reported in experimental studies on reading implies that the observational uncertainty of target location in reading is the same as the uncertainty in the prior knowledge about the distribution of target locations.

As reported in Chapter 3, the Bayesian model for saccade targeting could account for the experimental findings by assuming that, in comparison to the normal reading condition, readers obtained more precise sensory information during saccade planning when texts were read from right to left. At the same time, readers maintained their prior knowledge about the distributions of target locations during reading. Based on similar assumptions, the explanation can be extended to describe the simultaneous increased precision and accuracy observed in the conditions where letter sequences were inverted in the study reported in Chapter 2. Interestingly, under the assumption that the sensory likelihood could remain constant in certain conditions, the Bayesian model for saccade planning would predict that improvement in the variance of the prior distributions would have resulted in improved precision of the saccade targeting but a greater systematic error simultaneously. Similar changes could be observed in the conditions where letter position information was kept intact (e.g., mirrored-letter and scrambled-letter conditions reported in Chapter 2). Nonetheless, further model fittings should be conducted to confirm this prediction.

It is plausible to speculate that when the newly confronted unusual reading condition does not deviate from the learned reading condition, i.e., words were written and read in a left-to-right manner, readers tend to rely on the prior knowledge about the distributions of target locations during reading while integrating the newly acquired information to update the previously learned information. However, when the new condition deviates from the normal reading condition and requires detailed visual information, readers rely on obtaining sensory information about the (new) target location while maintaining the previously known information. The newly acquired information would be integrated into the prior knowledge for future use.

5.2 Implications for future research

5.2.1 Implications for reading experiments

The studies reported in this thesis demonstrated that the oculomotor system can adapt to specific changes in reading conditions. Since this thesis focuses on the oculomotor performance under different manipulations of text layout, exploring the effect of orthographic manipulations on other processes involved in reading such as the processing span should deliver new insights for understanding the underlying processes during reading. The effect of orthographic manipulations on perceptual span during reading can be experimentally tested by applying the moving window paradigm (see Starr & Rayner, 2001, for review) to capture the effective window size for reading texts with manipulated orthographic.

Furthermore, saccades during reading can be precise and accurate at the same time when the reading condition requires it to do so. It would be interesting for future studies to explore the performance of the oculomotor system under different instructions, e.g., proofreading, which might involve more precise saccade targeting during reading for the typical left-to-right reading. Previous studies have addressed the effect of the reading instruction on the oculomotor control during reading but with the strong focus on temporal aspects of the eye movement measures (Radach et al., 2008; Kaakinen & Hyönä, 2010; Schotter et al., 2014). While Radach et al. (2008) reported only minor effects of instructions (word-verification versus comprehension reading) on global landing positions on words, Kaakinen & Hyönä (2010) reported a left shift of fixation landing positions under proofreading instruction. However, a comprehensive analysis of the systematic and random components of oculomotor error under different instructions is currently missing.

The general improvement of the oculomotor performance reported in the two experimental studies (Chapter 2 and Chapter 3) is associated with the prolonged fixation durations due to the manipulations applied. It is unclear whether the prolongation is associated with the increased processing load or the time needed to plan more precise saccades. Numerous studies focused on the temporal and spatial aspects of incoming fixations landing on the target words, e.g., high versus low-frequency words (Lavigne et al., 2000; Nuthmann, 2006; Vonk et al., 2000). It would be interesting for future studies to investigate the effect of increased cognitive load on currently fixated words on the performance of saccade targeting on the subsequent words. If the currently fixated words were difficult to process and require more resources, the saccade targeting process would be impaired, reflected in the higher variance of fixation positions on the neighboring word $N + 1$. However, if the additional time was needed for the goal-oriented saccade programming, the distribution of fixation positions on the subsequent word $N + 1$ should have a lower variance.

The experimental findings reported in this thesis can be interpreted against the backdrop of the process-oriented Bayesian model for saccade targeting that makes explicit assumptions and predictions regarding the amount and sources of oculomotor errors observed in reading. Nevertheless, further experimental studies should focus on testing the prediction of the Bayesian model for saccade targeting.

Finally, further studies focusing on the oculomotor performance during reading should reconsider the method used to estimate the proxies for the intended landing positions within-word and take the mislocated fixations into the account. Following the assumption that within-word fixation locations within a word approximate a Gaussian distribution, plausible proxies can be obtained by fitting a normal distribution to the data, either independently for each word-based distribution (e.g., the Gaussian fitting method) or by assuming that all distributions are mutually informed (e.g., the Bayesian fitting method). While the simple arithmetic mean method manages to describe the global distribution of landing positions within words, it shows the strongest systematic bias in estimating the slope parameter λ of the landing-position function, which serves as the most important finding to quantify the oculomotor performance during reading.

5.2.2 Implications for computational reading models

The experimental studies reported in this thesis showed that changes in text layouts and reading direction resulted in changes in eye movement patterns specific to the manipulation type, both in temporal and spatial aspects of eye movement measures associated with the underlying cognitive and oculomotor processes during reading. These findings should posit a challenge for the optimization of computational reading models. Since notable computational reading models assume that both cognitive and oculomotor processes are independent, they are challenged to integrate the cognitive and oculomotor processing involved in the oculomotor control of eye movements during reading. At the same time, these models are challenged to fit the specific changes observed in reading behavior across tasks.

Furthermore, the computational reading models assume that the pattern of saccadic errors in reading is highly robust by incorporating the systematic and random components of saccades based on the mathematical formulation and numerical values reported by McConkie et al. (1988). Nonetheless, the experimental findings reported in this thesis indicated that the oculomotor system is highly adaptive and the saccadic errors can be modulated during reading to a large extent. This emphasizes that reading models could be improved by implementing process-oriented assumptions for the saccade-planning process. The Bayesian model for saccade planning (Engbert & Krügel, 2010; Krügel & Engbert, 2014) represents a suitable candidate to be integrated into these computational reading models. Additionally, both cognitive and oculomotor model parameters should be estimated simultaneously during model fitting (e.g., Rabe et al., 2019).

5.3 Final conclusion

Investigating the oculomotor control during reading is not trivial because reading is a complex process and the eye movement data are not error-free. A signature of the oculomotor system is the within-word landing positions. The oculomotor system is very robust and only through the exploration of different eye movement measures (e.g., landing location of single fixations, word-to-word forward saccades, refixations) and the application of precise estimation method (e.g., fitting Gaussian distribution function into the data points), the effect of experimental manipulation can be captured. Additionally, research focusing on the role of the oculomotor system during reading should take mislocated fixations into account when estimating the proxies for the intended within-word fixation positions. Contrary to the common assumption, the oculomotor system is adaptive to various reading conditions and, when required, goal-oriented saccades can be generated. Interestingly, both random and systematic components of oculomotor errors can be reduced simultaneously, suggesting that the two error components are not independent. According to the Bayesian saccade planning model, the increased sensory information is responsible for the improvement of saccade planning observed. The development of mathematical reading models should reconsider their implementation of the formulation proposed by McConkie et al. (1988) to represent the oculomotor system in saccade targeting because it does not provide a theoretical explanation on the findings reported in this thesis, e.g., the reduced (systematic) launch-site effect. The Bayesian saccade planning model is one candidate to be considered to represent the oculomotor system in the mathematical reading models because it provides explicit assumptions on the amount and sources of the oculomotor errors and can be experimentally tested.

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