Eye movement control during reading: Factors and principles of computing the word center for saccade planning

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Zusammenfassung

Lesen ist eine komplexe kognitive Aufgabe, die auf der Analyse visueller Reize beruht. Aufgrund der Physiologie des Auges kann jedoch nur eine kleine Anzahl von Buchstaben um den Fixationsort mit hoher visueller Genauigkeit wahrgenommen werden, während die Sichtbarkeit der Buchstaben und Wörter außerhalb der sogenannten fovealen Zone mit zunehmender Entfernung stark abnimmt. Während des Lesens sind deshalb sakkadische Augenbewegungen erforderlich, um die Fovea zur visuellen Identifikation neuer Wörter wiederholt innerhalb des Textes zu verschieben.

Auch innerhalb eines direkt betrachteten Wortes erlauben mittige Fixationsorte eine effizientere Wortverarbeitung als randnahe Blickpositionen (O'Regan, 1981; Brysbaert, Vitu, and Schroyens, 1996). Die meisten Lesemodelle nehmen deshalb an, dass Leser auf die Mitte von Worten zielen (für eine Übersicht siehe Reichle, Rayner, & Pollatsek, 2003). Es zeigt sich aber, dass Landepositionen innerhalb von Wörtern im Lesen von der Distanz der Startposition einer Sakkade zur Mitte des Zielwortes moduliert werden (McConkie, Kerr, Reddix, & Zola, 1988). Noch ist weitgehend unklar, wie Leser die Mitte eines Zielwortes identifizieren. Es fehlt an computationalen Modellen die die sensumotorische Umwandlung der Auswahl eines Zielwortes in eine räumliche Koordinate der Wortmitte beschreiben.

Wir präsentieren hier eine Reihe von drei Studien, die darauf abzielen, das Wissen über die Berechnung von Sakkadenzielkoordinaten im Lesen zu erweitern. In einer umfangreichen Korpusanalyse identifizerten wir zunächst das Überspringen von Wörtern als weiteren wichtigen Faktor bei der Sakkadenprogrammierung, der einen ähnlich systematischen und großen Effekt auf die Landepositionen hat wie die Startpositionen der Sakkaden. Anschließend zeigen wir Ergebnisse eines einfachen Sakkadenexperiments, welche nahelegen, dass der Effekt übersprungener Wörter das Ergebnis hoch automatisierter perzeptueller Prozesse ist, die wesentlich auf der Bestimmung von Leerzeichen zwischen Wörtern basieren. Schließlich präsentieren wir ein Bayesianisches Modell der Berechnung von Wortmitten auf der Grundlage der primären sensorischen Erfassungen von Leerzeichen zwischen Wörtern. Wir zeigen, dass das Modell gleichzeitig Effekte der Startposition und des Sakkadentyps erklärt. Unsere Arbeiten zeigen, dass die Berechnung räumlicher Koordinaten für die Sakkadenprogrammierung im Lesen auf einer komplexen Schätzung der Wortmitte anhand unvollständiger sensorischer Informationen beruht, die zu systematischen Abweichungen von der tatsächlichen Wortmitte führt. Unsere Ergebnisse haben wichtige Folgen für gegenwärtige Lesemodelle und für die experimentelle Leseforschung.

Abstract

Reading is a complex cognitive task based on the analyses of visual stimuli. Due to the physiology of the eye, only a small number of letters around the fixation position can be extracted with high visual acuity, while the visibility of words and letters outside this so-called foveal region quickly drops with increasing eccentricity. As a consequence, saccadic eye movements are needed to repeatedly shift the fovea to new words for visual word identification during reading.

Moreover, even within a foveated word fixation positions near the word center are superior to other fixation positions for efficient word recognition (O'Regan, 1981; Brysbaert, Vitu, and Schroyens, 1996). Thus, most reading theories assume that readers aim specifically at word centers during reading (for a review see Reichle, Rayner, & Pollatsek, 2003). However, saccades' landing positions within words during reading are in fact systematically modulated by the distance of the launch site from the word center (McConkie, Kerr, Reddix, & Zola, 1988). In general, it is largely unknown how readers identify the center of upcoming target words and there is no computational model of the sensorimotor translation of the decision for a target word into spatial word center coordinates.

Here we present a series of three studies which aim at advancing the current knowledge about the computation of saccade target coordinates during saccade planning in reading. Based on a large corpus analyses, we firstly identified word skipping as a further factor beyond the launch-site distance with a likewise systematic and surprisingly large effect on within-word landing positions. Most importantly, we found that the end points of saccades after skipped word are shifted two and more letters to the left as compared to one-step saccades (i.e., from word *N* to word *N+1*) with equal launch-site distances. Then we present evidence from a single saccade experiment suggesting that the word-skipping effect results from highly automatic low-level perceptual processes, which are essentially based on the localization of blank spaces between words. Finally, in the third part, we present a Bayesian model of the computation of the word center from primary sensory measurements of inter-word spaces. We demonstrate that the model simultaneously accounts for launch-site and saccade-type contingent modulations of within-word landing positions in reading. Our results show that the spatial saccade target during reading is the result of complex estimations of the word center based on incomplete sensory information, which also leads to specific systematic deviations of saccades' landing positions from the word center. Our results have important implications for current reading models and experimental reading research.

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1. Introduction

The importance of the cultural invention of reading and writing for the development of the human race can hardly be overestimated (Diringer, 1962; Ong, 1982). Taking a few thousand years from humans' early symbolic artifacts in 30000 B.C. to the first appearance of syntactic scripts in the ancient Middle East about 3000 B.C. to the development of the modern logographic or even later alphabetic writing systems (Marshack, 1972; Gelb, 1963; Senner; 1989; Olson, 1996), reading is a fairly late development in human history and general literacy is not more than the blink of an eye. Thus, the human capacity for reading is based on brain functions which evolved long before humans learned to read. Today we are surrounded by written words and for most of us it is almost impossible not to read incessantly. In Huey's words, understanding how we read means "to unravel the tangled story of the most remarkable specific performance that civilization has learned in all its history" (1908, p. 6).

For cognitive psychologists, reading provides an excellent experimental venue for investigating complex human information processing under ecologically valid conditions (Radach & Kennedy, 2004; Reichle, Pollatsek, Fisher, & Rayner, 1998). Since reading is based on the analysis of a visual stimulus it is strictly constrained by the limitations of the visual system, particularly the sharp decline of visual acuity outside the fovea (i.e., the small region of the retina which encompasses approximately two degrees of visual angle in the center of vision). Thus, while the primary goal of reading is the decoding of the written symbols and the construction of a meaningful interpretation of the written text, eye movements are necessary to shift words into the fovea for detailed analyses. Eye behavior during reading is characterized by an alternating sequence of fast movements called saccades, which abruptly bring the eyes to new locations in the line of text, and periods of relative stability of the eyes between any two saccades called fixations. During saccades perception is suppressed and new information can be obtained only during fixations (Matin, 1974). Such fixation durations are typically about 200-250ms and average saccades move the eyes about 6-9 letter spaces further into the text (Rayner, 1998). However, there is large variability within both fixation durations and saccade amplitudes. Both the *when*- and *where*-decisions of eye-movement control seem highly sensitive to low-level visuo-motor and high-level cognitive factors (for comprehensive reviews see for example Rayner, 1998; 2009; Radach & Kennedy, 2004; 2013; Hyönä, 2011). For example, fixation durations are influenced by the length of a word (i.e., a low-level visual property) but also by its predictability from the previous sentence context (i.e., a high-level cognitive factor, see Kliegl, Grabner, Rolfs, &

Engbert, 2004; Kliegl, Nuthmann, & Engbert, 2006). Thus, eye-movements can give rise to the ongoing moment-to-moment processes during reading such as visual word recognition, linguistic processes, reasoning, ambiguity resolution, attention- and memory processes and visuo-motor saccade planning by means of their temporal and spatial consequences for eye-movement control.

The present thesis is mainly related to the *where* of eye fixations during reading. Before a motor program is generated and sent to the eye, spatial coordinates of the saccade target position need to be computed. Here we aim at identifying the main low-level visual factors and computational principles which contribute to the spatial planning of saccades during reading. Finally, we propose a new model of the computation of saccade target coordinates during reading based on the sensory localization of spaces between words and Bayesian inference principles. In the following sections of chapter 1 we provide a selective introduction of central concepts relevant for the subsequent chapters and give an overview of the present studies.

1.1 The word-center targeting assumption in reading

There is a broad consensus in the literature and among current reading theories that the control of eye-movements during reading is generally word based and that readers send their eyes to particular selected target words when proceeding in a line of text (Rayner, 1979; McConkie et al., 1988; O'Regan & Levy-Schoen, 1987; Reichle, Rayner, & Pollatsek, 1999; Radach & McConkie, 1998; Radach & Kennedy, 2013; but see Vitu, 2003, 2008, 2011; McConkie & Yang, 2003; Yang & McConkie, 2004; Yang, 2006 for a different perspective). Moreover, it is widely assumed that the centers of target words serve as the functional within-word target positions, i.e., that readers aim at word centers. In the following we will outline the evidence supporting the word-center targeting assumption in reading.

One line of arguments focuses on the reason why the central fixation location within words during reading may be optimal, hence, why it would be generally reasonable to aim at word centers during reading. O'Regan (1981) wondered whether the quick drop of visual acuity on either side outside the current fixation position, would constrain readers' ability to recognize the fixated word. In particular, he asked whether the central fixation position within a printed word would lead to optimal recognition performances because such a fixation position maximizes the number of letters of the word, which falls into the high acuity foveal region of the eye. In subsequent studies, O'Regan and colleagues (O'Regan, Lévy-Schoen, Pynte, &

Brugaillère, 1984; O'Regan & Levy-Schoen, 1987) found that a first fixation position near the center of the words leads to a substantial reduction of the probability to re-fixate the word and to a reduction of the total time subjects spent reading the word. Furthermore, they demonstrated that a fixation position at the word center maximizes the probability of correctly recognizing a very briefly displayed word. From this they concluded that the word center is indeed the *optimal viewing position* (OVP) for the initial fixation on a printed word. Since then the optimal viewing position effect on the speed and the accuracy of visual word recognition has been demonstrated in an impressively large number of studies employing different tasks like word naming, perceptual identification and lexical-decision tasks and across a number of different languages (Brysbaert, 1994; Brysbaert, Vitu, & Schroyens, 1996; Farid, & Grainger, 1996; Nazir, O'Regan, & Jacobs, 1991; Nazir, Heller, & Sussmann, 1992; O'Regan, 1981, 1990; 1992; Pynte, Kennedy, & Murray, 1991; Stevens, & Grainger, 2003; Van der Haegen, Drieghe, & Brysbaert, 2010; see Brysbaert & Nazir, 2005 for a review).

A second line of evidence comes from observations made from eye-movement behavior in more natural reading contexts, which suggest that readers' saccades are indeed aimed at the middle of words. First of all, and prior to the discovery of the OVP, Rayner (1979) had discovered that the distribution of saccades' initial landing positions within words generally show a pronounced peak slightly left of the center of the words. This finding of a *preferred viewing position* (PVP) within words was primarily interpreted as evidence for the word-based nature of eye-movement control during reading. However, the fact that the PVP within words during normal reading and the OVP for foveal word processing refer to largely equivalent locations near the word center lends support to the assumption that readers intentionally aim at word centers. Second, the optimal viewing position effect, i.e., the fact that written words are identified most efficiently when the fixation position is near the word center, was also found to be true for the processing of words in continuous text reading, albeit substantially weaker than for the visual inspection of isolated words (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Vitu, O'Regan, & Mittau, 1990). Interestingly, under normal text reading conditions, initial fixation locations near word centers lead to minimized probability of refixations on the same word but, contradicting expectations, to the largest fixation durations, i.e., fixation durations further away from the center and closer to the boundaries are shorter (Vitu, McConkie, Kerr, & O'Regan, 2001; O'Regan, Vitu, Radach, & Kerr, 1994). However, this *inverted optimal viewing position* (IOVP, Vitu et al., 2001) effect for fixation duration on words in normal reading may be a consequence of a relatively high proportion of immediately error-corrected mislocated fixations near the word boundaries (Nuthmann, Engbert, & Kliegl, 2005).

A further, and probably the most important, piece of evidence supporting the word-center targeting assumption was discovered by McConkie, Kerr, Reddix, and Zola (1988). McConkie and his colleagues found two pivotal factors which influence saccades' amplitudes during reading: the distance of the target word from the location at which the saccade is launched and the length of the target word. Interestingly, when they computed the launch site of saccades and the landing site of saccades both as distances from the center of the target words, the effect of word length largely disappeared. That is, saccades during reading move further into long words than into short words but finally land at similar positions relative to the center of these words (when the distance of the launch-site from the word center is controlled for). According to McConkie et al. (1988), this confirms that the centers of selected target words serve as functional within-word target positions for the word-based control of saccadic eye movements during reading.

Thus, based on a number of robust experimental findings, the word-center targeting assumption has now become a widely shared theoretical position (Rayner, 1998). However, it remains largely unclear how readers identify the word center in the parafovea during the processing of the foveated word *N* and how the saccadic system computes the spatial coordinates for programming an efficient motor command (McConkie et al., 1988; Rayner, Reichle, & Pollatsek, 1998). Current computational eye-movement control models in reading typically make no assumptions about the sensory identification of the word center. The central goal of this thesis is to shed more light on these processes. In particular, we aim at both the identification of variables which may have an influence on the computation of spatial saccade target positions and the development of a psychologically sound process-oriented computational model of the sensorimotor processes during saccade programming in reading. It follows from the word-center targeting assumption that saccadic landing positions within words during reading, which don't match the word center, likely represent oculomotor errors. At the same time, saccadic landing site errors open a window to the scientific examination of the underlying sensorimotor processes during saccade planning in reading, since reliable oculomotor errors and their correlation with other variables potentially reveal fundamental human sensorimotor limitations as well as specific constraints of the saccade planning processes in reading. In the following section we will focus on the random and systematic variability of saccades' initial landing positions within words during reading.

1.2 Systematic and random landing position errors in reading

Contrary to the assumption of a clearly defined target position during reading there is surprisingly large variability within saccades' initial within-word landing positions. On the one hand, since human motor systems are fundamentally unable to intentionally produce exact copies of movements (Harris & Wolpert, 1998), saccade amplitudes are inevitably subject to random error. As a consequence, saccadic landing positions within words in reading vary randomly, according to a Gaussian distribution, around a pronounced mean landing position. It has been found that the random-error component, as reflected by the variance of saccades' landing-position distributions, increase with the distance of target words (McConkie et al., 1988). Interestingly, the random variability of saccadic end points in reading is substantially larger than in simpler goal-directed eye-movement tasks (e.g., Kowler & Blaser, 1995; Kapoula, 1985). In reading, Gaussian within-word landing-position distributions are surprisingly broad and their tails are often obviously truncated at the word boundaries, which artificially constrain the observation of landing positions of a certain word-based distribution in continuous reading. However, the truncated tails indicate that the landing distributions often substantially overlap with word neighbors of the actual target word and, in turn, this suggests that a significant proportion of saccades erroneously land at unintended words (McConkie et al., 1988). Engbert and Nuthmann (2008) used advanced computational techniques to numerically approximate the proportion of such *mislocated fixations* by extrapolating the truncated landing distributions from a large reading experiment. According to their analyses, nearly one third of all fixations during reading are affected by oculomotor errors which are large enough to cause a complete missing of the intended word.

However, saccades' landing positions are not only determined by the word center and random perturbations of saccade trajectories. In general, readers most often initially fixate at the PVP (Rayner, 1979). However, the closeness of agreement between the average initial landing position and the word center is in fact a function of the distance of the saccadic launch site from the center of the target word[1]. In a groundbreaking work, McConkie and colleagues (McConkie et al., 1988) discovered that the eyes tend to systematically overshoot

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[1] Although it is generally accepted that saccade amplitudes during reading are mainly determined by low-level visual factors such as word length and launch site, a number of studies suggest that saccade amplitudes are to a small degree also influenced by high-level linguistic word properties. For example, Yan, Zhou, Shu, Yusupu, Miao, Krügel, & Kliegl (2014) recently showed that saccadic landing positions are modulated by aspects of the morphological structure of words (number of suffixes) during the reading of Uighur scripts. A thorough overview of *cognitive landing-site effects* (Underwood & Radach, 1998) is provided by Radach, Inhoff and Heller (2004).

word centers which are located at short distances, i.e., no more than approximately five or six letter positions from the launch site of the saccade, and, in contrast, to systematically undershoot word centers which are more distant than approximately seven letters. Most importantly, McConkie and colleagues showed that there is an approximately linear and fairly word-length independent relationship between the center-based launch-site distance and the distance of the saccadic landing site from the word center. According to McConkie et al.'s estimates, saccade mean landing positions are systematically shifted half a letter position to the left when the distance of the launch site from the word center increases by one letter. The so-called *linear landing-position function* (Radach & McConkie, 1998) represents a robust oculomotor phenomenon in reading (McConkie et al., 1988; Radach & McConkie, 1998; Nuthmann et al., 2005; Rayner, Sereno, & Raney, 1996). Two aspects of the landing-position function are particularly worthy of note: Firstly, there is an optimal launch-site distance from which an average saccade lands fairly accurate at the word center, which is approximately six or seven letters (McConkie et al., 1988 for English readers) or between five to six letters (Nuthmann et al., 2005 for German readers) to the left of the word center. McConkie and his co-workers (1988) called this the *point of equality*, because from this position the over- and undershooting of word centers results solely from random errors and thus with equal likelihood.

The second key aspect is the slope of the linear regression function, which characterizes the size of the systematic launch-site contingent saccadic error. As McConkie and colleagues (1988) pointed out, a flat linear landing position function, i.e., a slope value of zero, can be expected if the oculomotor system responds perfectly well to changes of the distances of target-word centers with a fully consistent accommodation of the average saccade amplitudes. As a result no systematic launch-site contingent bias would occur and saccades from different launch-site distances would be expected to land at the same positions within words. The other extreme, i.e., a constant saccade length with no launch-site contingent modulations of saccade amplitudes would generate a slope of one, because any change in the launch-site distance would be accompanied by a change of the same size in the landing position. However, slope values between these two extreme cases suggest that saccade lengths are adapted to the distance of word centers but at the same time also inhere a systematic bias towards a constant length, which leads to the occurrence of systematic hyper- and hypometric saccades to near or distant word centers. A slope closer to one indicates a stronger bias and larger systematic oculomotor error. McConkie et al. (1988) and Nuthmann et al. (2005) consistently reported a numerical slope value of approximately 0.5 for English and German readers, which means that any increase of the center-based launch-site distance of a saccade leads to a left shift of the average landing position of half the size of the change in the launch-site distance. Thus, saccade amplitudes during reading exhibit a substantial systematic bias toward a constant saccade length.

1.3 The oculomotor range-error model: The dominant interpretation of the launch-site effect in reading

The systematic tendency towards an average saccade length is certainly among the most important oculomotor effects in reading. Most of the current computational models of eye-movement control (Reichle et al., 2003 for an overview) employ McConkie et al.'s (1988) estimates of the linear landing position function to approximate saccades' mean landing positions within words. Following McConkie and colleagues' (1988) interpretation, which refers to prior work of Kapoula (1985) and Poulton (1981), the dominant interpretation of the launch-site effect is that of a "manifestation of a basic principle of controlled muscle movement" (McConkie et al., 1988, p. 1116) and signature of a saccadic *range error*. But what is that supposed to mean? Originally, the term range effect refers in a very general sense to the phenomenon that the range of potentially relevant stimulus attributes or response alternatives which are employed in a particular task may systematically influence responses to individual stimuli. The central assumption is that there is some kind of transfer from the experience of general properties of a task-set configuration into the individual behavior. In other words, the range-error concept postulates that individual human responses are not necessarily fully determined by qualities of a physically present stimulus or experimental condition. Range effects have been reported in a broad variety of tasks such as time perception, sensory judgments, memory scanning, motor tasks or search tasks and, furthermore, different kinds of biases have been considered as being representative for the range-error phenomenon in general (Poulton, 1973; 1975; 1979; 1981; Stevens & Greenbaum, 1966; Stevens & Guirao, 1967; Slack, 1953; Hollingworth, 1910). Hollingworth (1909; 1910) provided an early experimental demonstration and first profound analysis of the main characteristics of a central-tendency bias comparable to the launch-site effect in reading. He reported that subjects in two different tasks, arm movements (Hollingworth, 1909) and sensory judgments of sizes of squares (Hollingworth, 1910), systematically tend to overestimate small stimulus magnitudes and to systematically underestimate large magnitudes. Corresponding to McConkie et al.'s (1988) *point of equality*, Hollingworth

(1910) reported the observation of an *indifference point* (*I.P.*) around the mean of the stimulus magnitudes employed in his experiments, at which no systematic error occurred. Hollingworth (1910) postulated that the I.P. “is a function of the series limits of the stimuli employed” (p. 461), and consequently, that “the same absolute magnitude may be either an I.P., or effected with a positive constant error, or with a negative constant error, according to the particular range or section in which it occurs” (p. 462). With this notion, Hollingworth already proposed the key assumptions of the range-error concept, which was established half a century later.

However, the success of the range-error interpretation for saccades in reading rests mainly on a study by Kapoula (1985, but see also Kapoula & Robinson, 1986), who reported two experiments in which subjects made goal-directed saccades to single targets which appeared randomly at one out of five possible target-position eccentricities. Most importantly, different but partially overlapping sets of target eccentricities were employed in the two experiments (eccentricities of 2.7° to 9.5° in experiment one; eccentricities of 7° to 21.9° in experiment two). In both experiments, a small saccadic central-tendency bias was found. Consistent with the range-error theory, systematic over- and undershoots of true target positions occurred specifically at those targets, which appeared at either the near or far ends of the range of eccentricities in the respective experiment. For the 7° target for example, the systematic error changed from undershoot in the first experiment into an overshoot in the second experiment. Above all, particularly this reversal of the direction of the systematic error according to the range of the entirety of target eccentricities in the experiments was interpreted as evidence for a range effect in the human saccadic system. Furthermore, Poulton (1981) suggested that this kind of range effect, i.e., the bias of human motor movements towards an average length, represents a *fundamental law of motor skills*, which probably emerges in any motor task and thus, also in saccadic eye movements. Interestingly, a different view was taken by Hollingworth (1909; 1910), who interpreted the central-tendency bias primarily as a *law of immediate perception* based on the fact that a qualitatively similar bias occurred in tasks with and without a motor component.

Nevertheless, based on the work of Kapoula (1985), Poulton (1981) and, finally, McConkie et al. (1988), the launch-site contingent shift of saccades landing positions in reading is now widely interpreted as a primarily (oculo)motor range effect. Accordingly, it is assumed that the general variability of saccade amplitudes based on the range of different word-center distances generates a systematic tendency of the human saccadic system to produce saccades of an average length. However, the range-error concept doesn’t include specific assumptions about the underlying processes which would cause this kind of flexibility limitation, neither for human motor movements in general nor in particular for eye-movements. As a consequence of this poor explanatory power of the range-error concept it remains doubtful whether the strong launch-site effect in reading and the very small saccadic range error found by Kapoula (1985) indeed reflect a similar kind of saccadic error. Estimating linear regression functions from the launch-site contingent mean landing positions reported in Kapoula (1985, tables 1 and 2) reveal numerical slope values of the linear landing position functions of approximately 0.1, which is considerably smaller than the slope of 0.5 of the central-tendency bias in reading. Furthermore, the studies of Kapoula (1985) and Kapoula and Robinson (1986) have also been criticized for methodological issues such as their small sample sizes and other researchers have failed to replicate the saccadic range effect with similar basic oculomotor paradigms (Findlay, 1982; Vitu, 1991b)[2].

In the next section we provide a brief introduction into the framework of Bayesian decision theory (Berger, 1985) and describe a recent work by Engbert and Krügel (Engbert & Krügel, 2010), which demonstrates that the launch-site effect in reading is likely the result of an estimation of the true spatial position of the word center according to Bayes' rule during saccade planning. Engbert and Krügel's (2010) Bayesian model of saccade planning in reading is important for the present thesis because it shifts the explanatory level of the saccadic range error from the motor system to sensory processes and thus, it directly bears upon the main question of this thesis: How readers identify the word center for saccade programming. The principle of Bayesian estimation of saccade target positions is also an important aspect of the computational model of saccade planning in reading, which is presented in chapter 4.

1.4 Bayesian saccade planning: Shifting the focus on perceptual processes

Focusing on the sensory processing during saccade planning, a reader's sensorimotor system can be considered as an observer attempting to optimally estimate the true position of the word center based on noisy and ambiguous information (Ghahramani, Wolpert, & Jordan, 1997; Knill & Richards, 1996; Engbert & Krügel, 2010). This is, because human sensory

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[2] A systematic tendency of the eyes to move towards the cortically weighted *center of gravity* of the configuration of letters within an effective window to the right of the fixation has been proposed as an alternative framework to explain the relationship of saccades' launch sites and landing sites during reading (see Vitu, 1991a; 1991b; 2008; 2011). In the course of the present work, the relationship of our results and conclusions with the *center-of-gravity* approach is repeatedly discussed in different passages (see section 5.4 and pages 21 and 32).

information processing at all levels is fundamentally stochastic in nature (Faisal, Selen, & Wolpert, 2008). As an unavoidable consequence, any information, which humans gain from their sensors, is affected by noise, which leads to uncertainty and ambiguity as to the true state of the world. In effect, human motor control, including the control of eye-movements, is fundamentally based on estimates of true world states (Berniker & Körding, 2011) and constantly requires decisions in the presence of uncertainty (Wolpert & Landy, 2012) such as which possible position of the word center should be preferred over other potentially true word-center locations, given a particular sensory input. Bayesian decision theory (e.g., Jaynes, 1986; 2003; MacKay, 2003) has been proposed as an ideal framework to examine and formalize the process of estimation of environmental properties based on imperfect sensory input (Körding & Wolpert, 2004; Knill & Pouget, 2004; Ernst & Bülthoff, 2004). A key mechanism to counter noise within sensory data and, finally, to minimize uncertainty is to combine sensory information with sensory-independent knowledge, which was previously acquired by experience. In a sensorimotor task like the control of eye-movements during reading, in which a person has daily routine, it seems particularly plausible that the person possess profound knowledge about the statistics of the task. In the framework of Bayesian decision theory, this knowledge, which constitutes a strong a priori belief about the true state of the world, is called prior, while the term likelihood distinguishes newly acquired sensory information. Bayes' theorem provides the mathematically rigorous way to optimally integrate prior expectations and newly acquired sensory information so as to minimize the uncertainty of the combined estimate, which is called posterior.

Reading is a daily visuo-motor activity within a highly structured and well-constrained environment. Engbert and Krügel (2010) demonstrated that the sensory localization of word centers as functional saccade target positions is likely based on the principles of Bayesian inference. Engbert and Krügel (2010) assumed that skilled readers internalize a mental model of the typical distance and variability of word centers from saccade launch sites in normal reading. According to the Bayesian viewpoint this forms a prior over saccade target locations, i.e., an a priori probability distribution of word-center positions. However, while fixating at a particular word *N*, readers also gain new sensory information about the position of the word center of the upcoming target word. Based on the noisiness of the sensory signal, the likelihood can be expressed as a conditional probability of having a particular sensory impression, given each possible position of the word center. These assumptions constitute a situation in which an integration of prior and likelihood according to Bayes' rule leads to an optimal posterior estimate of the probability that the word center has a true position x, given the sensory information. The calculations according to Bayes' rule result in a posterior probability density with minimized variance, in other words they lead to an optimal estimator with minimized uncertainty. However, at the same time, the maximum-a-posteriori probability estimate, i.e., the peak of the posterior distribution systematically shifts towards the prior distribution. That is, the best estimate of the word center is located at a compromise location between the information derived from a highly flexible, real-time, but noisy sensory system and a solid, and virtually constant, memory-driven source of information. Engbert and Krügel (2010) showed that the distributions of saccades' initial landing sites in words in reading are compatible with the assumption that readers optimize incomplete sensory information of the word center according to Bayesian principles when computing spatial target coordinates for saccade programming. According to their view, the launch-site contingent saccadic range error is a consequence of the proposed sensory processes during saccade planning and is, notably, a signature of optimization processes and Bayesian inference within the perceptual system. Thus, this shifts the level of explanation of the origins of the saccadic range-error in reading from a rather unspecific consideration as general law of motor skills (McConkie et al., 1988; Kapoula, 1985; Poulton, 1981) to a specific model of sensory information processing, which can furthermore be used to derive specific predictions about the size of the range error under different conditions (for further discussion of this point see section 5.4).

From a more general perspective, this demonstrates the importance of understanding how readers translate the selection of a specific target word into a specific spatial target coordinate. However, while Engbert and Krügel (2010) focus on the question of how an existing sensory likelihood of the word center can be modified to derive optimal decisions on saccadic motor commands, the question of how the sensory likelihood is established, i.e., how the word center is initially identified by the readers sensory system, is omitted. From this perspective, the Bayesian model of Engbert and Krügel (2010) sets the stage of the central issue of the present thesis, which is the sensory identification of the word center during reading. To foreshadow chapter 4, we will present a computational model of saccade planning during reading based on the initial sensory identification of blank spaces between words in which the principle of Bayesian estimation for eye-movement control during reading continuously constitutes a vital element of the model assumptions.

1.5 Overview of the present studies

The following chapters present a series of three studies addressing the spatial computation of saccade targets during reading. The studies combine different but complementary methodological approaches including corpus analyses, single-saccade experiments, numerical estimation techniques and computational modeling. In the following sections we briefly summarize the motivation and main results of each study.

1.5.1 Chapter 2: On the launch-site effect for skipped words during reading

In chapter 2 we challenged the limits of the oculomotor range-error model by comparing landing positions of one-step saccades and word-skipping saccades. One-step saccades (in the following also referred to as simple forward saccades or one-word saccades) are saccades from a currently fixated word *N* to the next word in reading direction, i.e., word *N+1*. Word-skipping saccades, on the other hand, refer to saccades which shift the reader's fixation position from word *N* directly to the next-but-one word *N+2*, while skipping over word *N+1*. Both types of eye movements are ubiquitous in reading (Rayner, 1998). Figure 1.1 illustrates why this comparison constitutes a particularly appealing test for the range-error model. Most importantly, the range of distances of the launch sites from the center of the target words overlap widely in both types of saccades. Thus, we were able to compare the landing positions of one-step saccades with those of word-skipping saccades which were launched from equal distances towards the center of their target words. The oculomotor range-error model, which employs the distance of the launch site as the sole determining factor for the resulting average landing position, makes a clear prediction: If we control for the distance of the launch site from the word center, no difference should be observed between the landing positions of one-step saccades and word-skipping saccades. On the other hand, even if we control for the distance of the launch site, one-step saccades and word-skipping saccades differ substantially in several other low-level perceptual aspects, most importantly in (I) the number of words, which are directly involved, (II) the number of blank spaces, which separate these words, (III) the length of the launch-site word *N* after the launch site. (see Figure 1.1). If these aspects play a major role for the control of saccades during reading, as is often suggested in the literature (Starr & Rayner, 2001; Rayner, 2009), it is likely that they lead to differences in readers' final eye positions after one-step saccades and after word-skipping saccades.

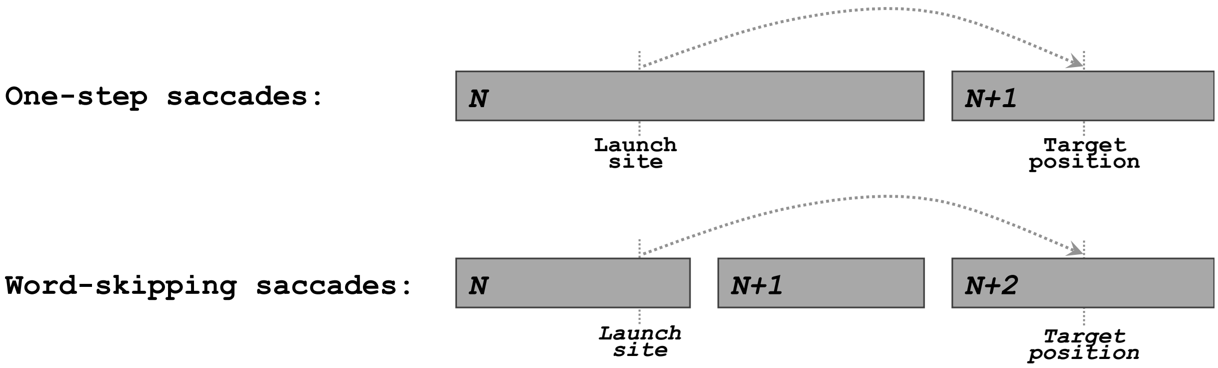

Figure 1.1. Schematic illustration of the visual configuration of words which are directly involved in the planning of one-step saccades or word-skipping saccades during reading. Gray bars represent words. The indices *N*, *N+1*, and *N+2* refer to the currently fixated word (i.e., word *N,* from which the saccade is launched), and to the first word (i.e., word *N+1*) or the second word (i.e., word *N+2*) to the right of word *N*. Dashed gray arrows illustrate the trajectories of hypothetically optimal saccades from words *N* to the target words *N+1* in one-step saccades or *N+2* in word-skipping saccades. According to the word-center targeting hypothesis, a hypothetically optimal saccade brings the eyes exactly to the center of the target word, which serves as the functional target position within the target word. Despite the intention to skip over word *N+1* in the word-skipping case the center of the target-word *N+2* is just as distant as is the center of the target word *N+1* in the above illustration of a one-step saccade.

We analyzed a large corpus of eye-movement recordings (Kliegl et al., 2006), which contains data from 275 adult skilled readers reading 144 sentences and which comprises more than 190000 recorded saccadic eye movements during normal sentence reading. This large database allowed us to systematically analyze initial within-word landing-position distributions of one-step saccades and word-skipping saccades in natural reading across a wide range of launch-site distances and word lengths. In contrast to assumptions of the oculomotor range-error model our analyses revealed surprisingly large differences between the distributions of landing positions of one-step and word-skipping saccades across the whole range of launch-site distances and word lengths. The results clearly demonstrate the limits of the range-error model in accounting for the variability of saccades landing positions in reading.

However, within-word landing-position distributions are biased by mislocated fixations (Stern, 1978; McConkie et al., 1988, Engbert & Nuthmann, 2008), which invites substantial doubt about the reliability of our results. Thus, the correction of landing-position distributions from mislocated fixations constitutes a second key aspect of chapter 2. Mislocated fixations result from saccades which erroneously land at unintended words next to the saccade's actual target word due to visuo-motor errors. Since the target words of individual saccades during normal reading remain typically unknown to the observer of the reading experiment, mislocated fixations cannot be individually distinguished from well-placed and intended fixations on a particular word. However, Engbert and Nuthmann (2008) demonstrated that it is possible to numerically approximate the proportions of mislocated fixation within individual landing-position distributions. Based on this approach we developed an improved estimation algorithm, which, most importantly, distinguishes one-step saccades from word-skipping saccades and which further employs a dramatically lower number of free parameters. After removing mislocated fixations from the landing distributions we still observed large differences between the landing sites of one-step saccades and word-skipping saccades which are at the same order of magnitude as the well-established effect of the launch-site distance. In particular, the average landing sites of word-skipping saccades were strongly biased towards the skipped word. Compared with one-step saccades of equally distant launch sites, the landing positions of word-skipping saccades lay consistently two or more letters to the left. Moreover, with word skipping the standard deviations of the distributions of saccades' landing positions increased by a factor of approximately two, i.e., the variability of landing position within the target words is much higher when words are skipped than when no word is skipped. Finally, word skipping strongly modulated the launch-site contingent changes of both saccades' mean landing positions and saccades' landing-site variability.

In summary, our findings revealed serious limitations of the oculomotor range-error model to account for saccades' landing positions in reading. Our results suggest that the visual configuration of the launch-site contiguous text region, and not just the distance of the target-word center, has a substantial impact on the average length and thus on the landing position of the saccades. This leads us to assume that a substantial amount of the variability of readers landing positions within words during reading stem from the computation of the saccade target, i.e., the determination of the spatial position of the center of the target word, based on low-level perceptual information and not solely from motor error in the execution of the saccadic movement.

1.5.2 Chapter 3: Fixation positions after skipping saccades: A single space makes a large difference.

In chapter 3 we aimed at clarifying whether the left-shift of saccades' landing positions after skipped words is limited to normal reading or whether we would be able to observe similar oculomotor behavior under non-reading conditions, too. For normal reading, our results from chapter 2 had clearly demonstrated that the remarkably large left-shift after skipped words is not just a curious exception that occurs when readers skip short function words, as suggested by Radach and McConkie (1998), but turned out to hold true for a wide range of target-word distances and word-length. However, we could not finally conclude that our findings revealed fundamental constraints of the oculomotor system or whether the left-shift reflects a general strategy associated with word skipping in reading, probably to facilitate the final processing of the skipped word as suggested by Radach and McConkie (1998; see also Radach, 1996). Obviously, this question has important implications for the further development of appropriate oculomotor models but is not easily answered with reading data alone.

As a consequence, we conducted a single saccade experiment to examine the skipping of letter strings under non-reading conditions. If saccades' landing-site bias towards the skipped words occurs exclusively during normal reading it would suggest that the effect is top-down controlled and voluntarily intended. However, if we could establish that the effect also occurs under non-reading conditions then we would gain strong support that the effect is a signature of more universal visuo-motor principles, which are likely triggered from low-level perceptual aspects of the visual configuration.

Subjects of this experiment were asked to read a group of three nouns. However, in order to read the words subjects were forced to launch an initial saccade from a string of x-letters to move their eyes to the first noun and to start reading. The string of X's, which varied in length across trials, carried no semantic information and was irrelevant except that it provided information about the position of the word group, which was always placed one blank space behind the end of the x-letter string. Most importantly, in half of the trials a single X-letter was removed from the string and its position was left blank so that the whole x-letter string appeared divided into two parts. In these trials, subjects' initial saccades had to skip over the second part of the divided string in order to approach the first noun as efficiently than in the control trials with a non-interrupted x-letter string. These artificial non-reading skipping trials over a string of X's constituted a situation very similar to the skipping of real words in normal reading in the sense that both cases share most of the relevant low-level aspects like the position of spaces between letter strings or the length of the launch-site and intermediate letter strings. On the other hand, and contrary to normal reading conditions, since the string of X's in the experiment was semantically completely meaningless no facilitation could be expected from strategically landing closer to the x-letter string, neither when it appears in two parts nor in one part. A shift of the first fixation position near or even on the x-letter string would here rather be detrimental to examine the three nouns most efficiently.

The results were very clear. Most importantly, it turned out that the general leftward relocation of saccadic end-points after skipping over an intervening word, which we had discovered in chapter 2, is not limited to normal reading but occurred also under non-reading conditions, and even more surprising, despite its detrimental effect on the task that was employed. This led us to conclude that the left-shift after skipped words is not under top-down control, difficult to avoid and not the result of a specific strategy with modified target positions in word skipping during reading. Furthermore, we also qualitatively replicated the launch-site distance effects on saccades' mean landing positions and random variability in both non-skipping and skipping trials. Interestingly, we also learned from more detailed analyses that the size of the skipping-contingent leftward shift was modulated as a function of the position of the removed X within the x-letter string, i.e., the distance of the gap within the string from the launch site, which suggests that this first single blank space in the direction of the saccade target plays a decisive role in the generation of the word-skipping effect.

Taken together, the result from this highly controlled single-saccade experiment lent strong support to the view that both the launch-site effect and the word-skipping effect are the results of low-level visuo-motor processes during saccade planning. We concluded that these processes constitute important boundary conditions for normal reading and provide benchmarks for future models of oculomotor control. Furthermore, we concluded that the first space after the fixated words is generally relevant for saccade planning during reading and is specifically involved in the generation of the effect of skipped words.

1.5.3 Chapter 4: A model of saccadic landing positions under the influence of sensory noise.

In chapter 4 we present a mathematical model of the processes involved in the computation of the center of the target word to serve as the functional target position for saccade planning during reading. To the best of our knowledge, the model proposes a first process-oriented answer to McConkie et al.'s (1988) fundamental question of "how this location [i.e., the center of the target word] can be positively identified“ (p. 1115) during the short duration of fixating and processing the current word *N* from which the upcoming saccade towards the next word center will be launched shortly. The model has two key aspects.

Firstly, based on previous research and the results from chapters 2 and 3 the model employs the idea that the spatial coordinates of the next target-word's center are estimated based on sensory measurements of blank spaces between words. In chapter 4, we propose explicit assumptions about which of the spaces are used and how they are integrated into a unified spatial representation of a pinpoint target position. More specifically, we assume that the first blank space to the right of a current fixation, i.e., the end of the currently fixated word, generally signalizes the onset of a spatially extended target region for the next progressive movement of the eyes into the line of text, while the space at the end of the target word is localized to estimate the outer limit of that region. In a second step, a computation of the spatial average of the spaces combines the two sensory signals and provides an initial sensory estimate of the word center. We show that this rule has interesting consequences for the computation of saccade targets in one-step saccades and word-skipping saccades particularly in that it determines a specific leftward bias of the target-position estimate towards the skipped word in word-skipping saccades. Secondly, we assume that readers optimize the noisy sensory estimate derived from the first step by combining it with prior, non-sensory knowledge according to Bayesian decision theory. With this assumption we continue the work of Engbert and Krügel (2010), who showed that the launch-site effect in reading is likely a consequence of Bayesian estimation of target positions during reading.

With computational simulations we demonstrate that the model is able to capture most of the effects which we identified in the studies described in chapters 2 and 3 as benchmarks for future models of oculomotor control. The model generates a launch-site contingent shift of saccades' average within-word landing positions, both in one-step saccades and in word-skipping saccades. The model generates the additional leftward shift in word-skipping saccades compared with one-step saccades for equally distant target positions. The model generates broader landing-position distributions in word-skipping saccades than in one-step saccades and a mostly constant variability of the landing distributions in one-step saccades across a wide range of launch-site distances. Finally, for word-skipping saccades the model correctly generates larger changes with changing launch-site distances both for saccades' average landing positions as well as for saccades' landing-site variability. Most importantly, the model replicates these effects all at the same time and in remarkably good quantitative agreement with the normal reading data.

2. On the launch-site effect for skipped words during reading

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Abstract. The launch-site effect, a systematic variation of within-word landing position as a function of launch-site distance, is among the most important oculomotor phenomena in reading. Here we show that the launch-site effect is strongly modulated in word skipping, a finding which is inconsistent with the view that the launch-site effect is caused by a saccadic-range error. We observe that distributions of landing positions in skipping saccades show an increased leftward shift compared to non-skipping saccades at equal launch-site distances. Using an improved algorithm for the estimation of mislocated fixations, we demonstrate the reliability of our results.

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2.1 Introduction

The control of eye movements during reading is constrained by boundary conditions of the oculomotor systems (Rayner, 1998; 2009). Most theories on eye movements in reading assume that readers aim at word centers to fixate at *optimal viewing positions* (OVP) within words (O'Regan & Lévy-Schoen, 1987; Radach & Kennedy, 2004; Rayner, 1998; Reichle et al., 1999; Reilly & O'Regan, 1998). However, landing positions within words turned out to be surprisingly broad (Rayner, 1979) and can be well approximated by normal distributions with tails truncated at word boundaries (McConkie et al., 1988). Furthermore, landing distributions show a pronounced peak, which is typically located halfway between word beginning and word center, i.e., there is a systematic tendency for the eyes to move to a preferred viewing location in reading (O'Regan, 1990; Rayner, 1979).

Most important for the current study, McConkie et al. (1988) found that within-word landing positions vary systematically as a linear function of the saccades' launch-site distances, i.e., the distance between the pre-saccadic fixation location and the beginning of the target word. More specifically, a leftward shift of the mean landing-site with a magnitude of half a character space was observed for each letter increment of the saccade's launch site distance. Interestingly, this launch-site effect interacts hardly with target word length, if the distances between launch-sites and landing sites are measured relative to word centers. Therefore, mean landing positions within words can be described by a linear landing-position function (Radach & McConkie, 1998) of the form

$$\Delta_{\mathrm{OVP}} = \lambda * (L_0 - L), \tag{2.1}$$

where L is the center-based launch-site distance and the resulting within-word mean landing position is given by Δ_{OVP} as the average displacement from the word center. A negative value of Δ_{OVP} indicates a leftward shift (undershoot) and a positive value indicates a rightward shift (overshoot) from the word center. The parameter L_0 in Eq. (2.1) was denoted as the *point of equality* by McConkie et al. (1988), because L_0 represents the optimal center-based launch-site distance, where the average displacement, Δ_{OVP}, from word center vanishes. The slope parameter λ is a quantitative measure for the strength of the launch-site effect. McConkie et al. (1988) and Nuthmann et al. (2005) reported an estimated slope of about 0.5 letter positions for readers of English and German texts respectively, i.e., for an increase of the launch-site distance L by one letter, the mean landing position moves half a letter from the word center in the direction of the displacement of L from L_0.

Based on their results, McConkie et al. (1988) argue in favor of two independent oculomotor error components, a random oculomotor placement error and a systematic saccadic-range error. The random placement error is assumed to reflect perceptuo-oculomotor inaccuracy in the execution of eye movements and adds random variability to the final eye position, which can be approximated by a Gaussian function. McConkie et al. (1988) and Nuthmann et al. (2005) reported a non-linear increase of the random error component for increasing launch distances.

The saccadic-range error represents a systematic launch-site contingent mean shift of landing positions, which was explained by McConkie et al. (1988) as a very general motor phenomenon of the range-error type (Poulton, 1974, 1981). The range-error concept postulates a fundamental tendency in human motor systems to bias directed motor movements towards a mean amplitude, which causes systematic undershoots of distal target locations and systematic overshoots of close target locations. Experimental evidence for a saccadic-range error in simple oculomotor targeting was reported by Kapoula (1985; see also Kapoula & Robinson, 1986), who demonstrated that participants slightly overshot close targets and undershot targets that were farther away than on average.

Following McConkie et al.’s (1988) important observations, current models of eye-movement control in reading incorporated the saccadic range-error principle to account for landing-position distributions within words (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005; Reichle, Warren, & McConnell, 2009; Reichle et al., 1999; Reilly & Radach, 2006). In a typical computational model, the word center is selected as the saccade target, but is modulated by the saccadic-range error and an additional random error component (see Reichle et al., 2003, for an overview).

The range-error concept was called into question by some authors. Most importantly, several oculomotor studies showed that saccadic landing positions are modified by the presence of additional visual stimuli other than the saccade target (Coëffé & O’Regan, 1987; Deubel, Wolf, & Hauske, 1984; Findlay, 1982; Vitu, 1991, 2008; Vitu, Lancelin, Jean, & Fariolia, 2006). Basically, these results demonstrate that the eyes were systematically deviated from a specific target location and land at an intermediate position between the distracter and the target. These results suggested the existence of low-level perceptual influences, which are called *center-of-gravity effect* or *global effect*, on saccade planning and/or execution. Since the visual distracter-target configuration of the word material in reading varies with the selection of a specific target location for the next eye movement, the center-of-gravity effect offers an alternative explanation for the launch-site effect in reading.

The motivation for the present study was to investigate the launch-site effect in the case of skipped words to find deviations from predictions of the saccadic-range error. Compared to a simple forward saccade (from word *N* to the next word *N + 1*), the physical configuration of words is very different in word skipping (i.e., a saccade from word *N* to word *N + 2*). Due to varying lengths of words *N* and words *N + 1*, launch-site distances overlap considerably between both cases. We use data from a large eye-movement corpus (Kliegl et al., 2006; see Section 2.2 for details) to investigate the launch-site effect in word skipping quantitatively. Limits of the range-error concept as an explanation of the launch-site effect in reading will turn out in the observed differences in landing-position distributions between normal forward saccades and word skipping (Section 2.3).

There was a previous study reporting a leftward shift of landing positions after word skipping by Radach and McConkie (1998). In addition to Radach and McConkie's (1998) incidental finding, we provide a fully quantitative analysis of the launch-site effect, which addresses the problem of mislocated fixations. As already mentioned by McConkie et al. (1988), experimental results on eye-movement data might be biased by the presence of mislocated fixations (i.e., saccades landing on word *N*, which were intended to target neighboring words). More technically, mislocated fixations are due to overlapping landing-position distributions from adjacent words. Recent progress on the estimation of the prevalence of mislocated fixations demonstrated that about 15–20% of all saccades land on unintended words (Engbert & Nuthmann, 2008; Engbert, Nuthmann, & Kliegl, 2007; Nuthmann et al., 2005). An application of these estimation techniques to the problem of word skipping will be used to demonstrate the reliability of our results (Section 2.4).

2.2 Experiments and methods

2.2.1 Participants

Analyses are based on eye-movement corpus data from nine experimental or quasi-experimental samples (Potsdam Sentence Corpus; PSC), reported in Kliegl et al. (2006). A total of 275 adults participated in the respective reading experiments. Age ranged from 16 to 84 years; all participants reported normal or corrected-to-normal vision. Subjects were paid 5–7 Euros or received study credit in exchange for participating in a 45–60-min session.

2.2.2 Apparatus, materials and procedure

Participants were seated in front of a computer screen with their heads supported on a chin rest. Immediately after the presentation of 10 practice sentences, 144 sentences appeared one after another on the horizontal centerline of the computer display (comprising a total of 1138 words). Readers' eye movements were recorded binocularly with sampling rates of either 250 Hz or 500 Hz (due to SR Research Eye Link I or Eye Link II recording systems). Calibrated fixation positions were logged with absolute gaze error less than 0.5° of visual angle (corresponding to about one letter).

2.2.3 Data pre-processing and curve fitting

Saccades were detected using a velocity-based algorithm (Engbert & Kliegl, 2003; Engbert & Mergenthaler, 2006). Only fixations from first-pass reading were used for subsequent analyses. Moreover, first and last fixations in sentences and fixations on first and last words of sentences were excluded. As a result the data set contained a total of 196582 valid fixations. (For a more detailed description of experimental procedure and data pre-processing see Kliegl et al., 2004; Kliegl et al., 2006). Truncated Gaussian curves were fitted on within-word fixation positions depending on word length, launch-site distance and sac- cade type using a grid search procedure (mean values and standard deviations were varied with a step size of 0.1 letter units).

2.3 Landing locations in word skipping

2.3.1 Landing-position distributions

A first glance at the distributions of within-word landing positions indicates qualitative differences between skipping and non-skipping cases. As an example, Figure 2.1 presents landing-position distributions on 4-, 6-, and 8-letter words in simple forward saccades (gray, solid line) and in skipping saccades (black, dashed line) for launch-site distances of 5–8 letter positions to the left of the beginning of the target word[3].

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[3] Note that the shortest word length in German is two characters. Together with adjacent spaces to the left and to the right of a two-letter word, the skipping of an intervening 2-letter word requires a minimal launch-site distance of 5 letters to the left of the beginning of the target word.

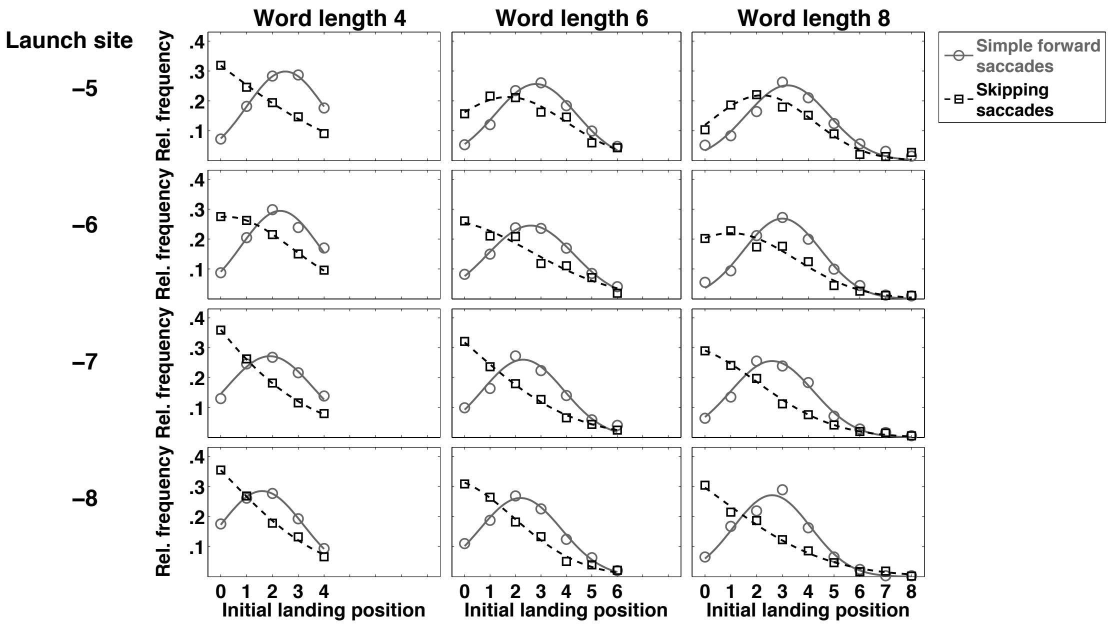

Figure 2.1. Distributions of within-word landing positions in simple forward saccades and in skipping saccades. Numbers along the horizontal axes indicate within-word character positions from the first to the last letter of the target word. The space to the left of the target word is denoted as letter position 0. Launch-site distance (negative) is computed as the number of letters between the launch position and the first letter of the target word.

Without exception, we found increased left-shifts of landing-position distributions in skipping saccades compared to simple forward saccades, although the corresponding saccades are launched from equidistant fixation positions. Based on fits of Gaussian curves to the highly left-shifted landing-position distributions in skipping saccades, we obtained mean landing positions, which often fall outside (to the left of) the word boundaries. Different from skipping cases, mean landing positions in simple forward saccades are generally located in the first half of the word considered (for numerical details see Tables 2.1 and 2.2 in Section 2.6). This result suggests that an extraordinarily large systematic oculomotor error in skipping saccades will produce many misguided saccades with high probability to undershoot the intended target word. We will address this issue in more detail in Section 2.4.

2.3.2 The landing-position function

For the systematic investigation of the launch-site effect across target-word lengths, we convert launch sites and landing positions into values relative to word centers of the target words (cf., McConkie et al., 1988). Using a plot of center-based landing sites as a function of center-based launch-site distance, the slope parameter λ and the optimal launch-site distance L_0, Eq. (2.1), can be computed directly using linear regression. In Figure 2.2a, center-based mean landing sites are plotted against center-based launch sites from simple forward saccades and from skipping saccades across word lengths of 4 - 9 characters.

We used a robust linear regression (MATLAB's robustfit function) to estimate saccade-type contingent linear landing-position functions (solid lines). We obtained numerical values λ = 0.28, L_0 = 5.11 for simple forward saccades and λ = 0.66, L_0 = 2.47 for skipping saccades. Obviously, there is a strong impact of word skipping on mean landing position, which affects both slope and intercept of the landing-position function. We find a much more pronounced leftward shift of the landing positions in skipping saccades. This result indicates a stronger tendency to undershoot the target word's center if the eyes skip an intervening word compared to the non-skipping case, but at equal launch-site distance. As a consequence, the estimated optimal launch-site distance, L_0, of the regression line is reduced by about 2.6 letter positions in the skipping case (L_0= 2.47) compared to the non-skipping case (L_0= 5.11). Note that the optimal launch-site distance in the skipping case cannot be observed in the experiment, i.e., almost all skipping saccades undershoot the target word's center. Moreover, we find a steeper slope parameter λ for the launch-site effect in skipping saccades. For every one-letter increment in launch-site distance, the average landing position of a simple forward saccade is shifted by about one third (0.28) of a letter to the left, whereas the same increase in launch-site distance for a skipping saccade produces a leftward shift of two third of a letter.

The most important implication of our results for the analysis of the launch-site effect in reading is that the slope parameter λ is dramatically overestimated, if skipping saccades are not excluded from the analysis. For example, McConkie et al. (1988) estimated a slope of about 0.5; however, our results show that the slope is either about 1/3 (for normal forward saccades) or 2/3 (for skipping saccades). As a consequence, the value of 0.5 represents the composite of two distinct saccade populations. Obviously, this finding will have substantial implications for theoretical models of the launch-site effect. In the next section, we address the influence of word skipping on the variances of landing-position distributions.

2.3.3 Random placement error

Landing-position distributions on words after skipping saccades are generally broader than on corresponding distributions after non-skipping saccades (Figure 2.3a). This finding suggests a larger random oculomotor error (or placement error) in skipping saccades compared to normal forward saccades. Across all launch-site contingent landing distributions, we obtained a mean standard deviation of 3.3 letters for skipping saccades compared to a value of 1.6 letters in simple forward saccades. Interestingly, the random error component in skipping saccades increases strongly with increasing launch-site distance, while a similar increase is absent for simple forward saccades (best fit linear functions are obtained as $SD = 1.36 - 0.03 * L$ for simple forward saccades and $SD = 1.08 - 0.21 * L$ for skipping saccades). Note, that McConkie et al. (1988) reported a non-linear launch-site contingent increase in saccades' landing-site variability of the form $SD = 1.318 + 0.000518 * L^3$, and that this result was qualitatively replicated by Nuthmann et al. (2005) for the present data set. Again, the decomposition of landing distributions contingent on saccade type (i.e., word skipping versus normal forward saccade) demonstrates that McConkie et al.'s (1988) findings are biased by averaging two more fundamental populations of saccades. According to our analysis, the slope of the regression line in simple forward saccades is negligible (however, the numerical value of 0.03 is statistically significant: $t(51) = -3.75$; $p < .001$). This result indicates a remarkable good capability of the human saccadic system to perform saccades across a wide range (3-13 characters) with minimal loss of accuracy. The decomposition of launch-site contingent landing-position distributions in reading based on cases of simple forward saccades and word skipping demonstrate remarkable effects of skipping on subsequent landing positions. Furthermore, these results suggest that saccade planning is not exclusively related to the launch-site distance towards the target word as predicted by the concept of the saccadic-range error (McConkie et al., 1988). However, our results might still be biased by misguided saccades, which landed on unintended words. This problem will be investigated in the next section.

2.4 The influence of mislocated fixations

It has been suggested by McConkie et al. (1988) that observed landing-position distributions are biased by mislocated fixations, which are generally defined as fixations on unintended words, i.e., a different word than the fixated word was selected as the intended target word. Using computational techniques to estimate overlapping landing-position distributions between adjacent words, it was demonstrated that mislocated fixations are indeed ubiquitous in reading and represent between 15% and 20% of all fixations (Engbert & Nuthmann, 2008; see also Nuthmann et al., 2005; Engbert et al., 2007). For example, as a potential explanation of the increased leftward shift in landing-position distributions after skippings, we could postulate that many word skippings represent mislocated fixations on word *N*+2, while word *N*+1 was the intended target word, i.e., overshoots would occur more frequent for short target words. In this section, we check the validity of the word-skipping effect reported in Section

2.3 by estimating the proportion of mislocated fixations from the experimental data and by correcting the corresponding landing-position distributions.

2.4.1 An improved algorithm for the estimation of mislocated fixations

The simultaneous computation of distributions of both mislocated and well-located fixations can be implemented by extrapolation of experimentally observed landing-position distributions to adjacent words using an iterative algorithm (Engbert & Nuthmann, 2008). The major problem of such an approach is that misguided saccades to unintended words bias both the experimentally observed landing distributions *and* the observed fixation probabilities for normal forward saccades, word skippings, and refixations. Therefore, Engbert and Nuthmann (2008) proposed a self-consistent estimation procedure that could replicate both landing-position distributions and fixation probabilities at the same time. This approach is self-consistent, since the fixation probabilities are consistent with the self-generated errors obtained from the within-word landing-position distributions. The estimation is based on an iterative algorithm where numerical simulations of a data-driven oculomotor model were applied (1) to decompose the distributions of within-word landing positions into well- and mislocated fixations and (2) to simultaneously adjust target-selection probabilities for simple forward saccades, skipping saccades, and refixations. As a result, estimations of the proportions of mislocated fixations within the oculomotor model converged to numerical values consistent with experimentally observed word-targeting probabilities and within-word landing-position distributions.

For the reliable estimation of mislocated fixations in the current study, we modified two properties of the original procedure as follows: First, the procedure developed by Engbert and Nuthmann (2008) did not capture effects of word skipping. Because our results strongly suggest that landing-position distributions are modulated by word skipping, and in order to test the reliability of the skipping effect if mislocated fixations are taken into account, we introduced saccade-type contingent parameters in the improved algorithm developed here. Second, in the original model 445 free parameters were identified (based on 1639 data points) to generate landing-position distributions for a wide range of possible combinations of launch-site distances and target-word lengths. To reduce the number of free parameters, we estimated linear fits for the parameters of all landing-position distributions (means and standard deviations) from saccade-type contingent data as presented in the first section of our results[4]. This procedure reduced the number of free parameters from 445 to 15 in the new version of the algorithm. Including these improvements, the self-consistent algorithm for the estimation of mislocated fixations consisted of 4 main steps:

1. Landing-position distributions were fitted by truncated Gaussian functions for each combination of word length, launch-site distance and saccade type. Saccade-type dependent linear regressions were computed for the launch-site effect on means and standard deviations of these distributions.
2. Based on the underlying probabilities for word-targeting, an oculomotor model was simulated to generate landing-position distributions using parameters obtained from the regression analyses in step 1.
3. The resulting simulated distributions from step 2 were used to estimate the proportions of mislocated fixations. Mislocated fixations were removed from the distributions.
4. Word-targeting probabilities were adjusted, so that the oculomotor model could reproduce the observed fixation probabilities.

This algorithm was repeated from steps 1 to 4 until the numerical values of landing-position distributions *and* word-targeting probabilities converged.

2.4.2 The launch-site effect in reading

After removing mislocated fixations from the experimentally observed landing-position distributions, we obtained unbiased numerical estimates for center-based mean landing sites (Figure 2.2b) and corrected standard deviations for landing-position distributions (Figure 2.3b). In Figure 2.2b, the pronounced leftward shift of mean landing positions in skipping saccades compared to normal forward saccades is still reliable even after the removal of mislocated fixations.

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[4] Note that we also conducted an alternative version of the model which additionally accounts for the supposed word-length effect on skipping saccades' mean landing sites and landing-site variability by drawing landing distributional parameters from launch-site, saccade-type *and* word-length contingent linear regression functions. However, the results obtained from this model were largely equivalent to those reported here.

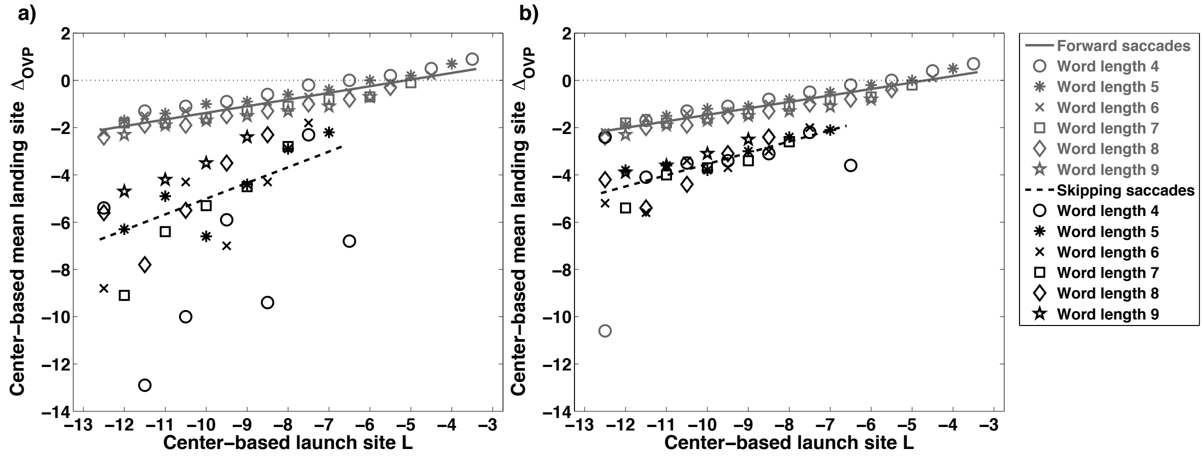

Figure 2.2. Center-based mean landing positions as a function of center-based launch-site distances for simple forward saccades and skipping saccades. Linear regressions indicate pronounced differences in both slope and intercept of the relations for the two conditions. (a) Estimated means of uncorrected landing-position distributions for different launch-sites, word-lengths, and saccade-types. (b) Estimated means of error-corrected landing-position distributions, where mislocated fixations were removed from the analysis.

However, the adjustment of the distributions for mislocated fixations shows that the effect of word skipping on mean landing positions is actually smaller than suggested by the analyses of uncorrected landing distributions. We found a substantial corrective rightward shift of mean landing positions in skipping saccades in the direction of the word center, which is even stronger for more distant launch-sites and demonstrates that the results obtained from raw data are substantially biased by mislocated fixations. More specifically, after removing mislocated fixations the slope λ of the associated linear landing-position function in skipping saccades is reduced from 0.66 to 0.48. In contrast, the slope in simple forward saccades remains nearly unaffected (reduction from 0.28 to 0.27). Thus, while there is a reliable difference of the launch-site effect between simple forward saccades and skipping saccades, uncorrected experimental data lead to an overestimation of this difference. Furthermore, we retained a reliable difference between optimal launch-site distances, L_0, for simple forward saccades (L_0=4.66) and skipping saccades (L_0=2.56).

The effect of the correction for mislocated fixations also affected our results on landing-site variability (Figure 2.3b). After removal of mislocated fixations from landing-position distributions, we still obtained reliable differences for simple forward saccades and for skipping saccades (best fit linear functions are obtained as $SD = 1.18 - 0.03 * L$ for simple forward saccades and $SD = 0.8 - 0.14 * L$ for skipping saccades). Thus, once again our findings from Section 2.3 are not artifacts of mislocated fixations. As a consequence, our results demonstrate that word skipping affects the variability of saccadic landing positions, which might be difficult to explain in the framework of the saccadic range error (McConkie et al., 1988). Even after correcting for mislocated fixations, we retained the slight (but significant; *t*(52)=-3.51, p<0.001) tendency to increased variability of landing positions in simple forward saccades when launch-site distance increases, while there is a clear increase of the variability with increasing launch-site distance for skipping saccades.

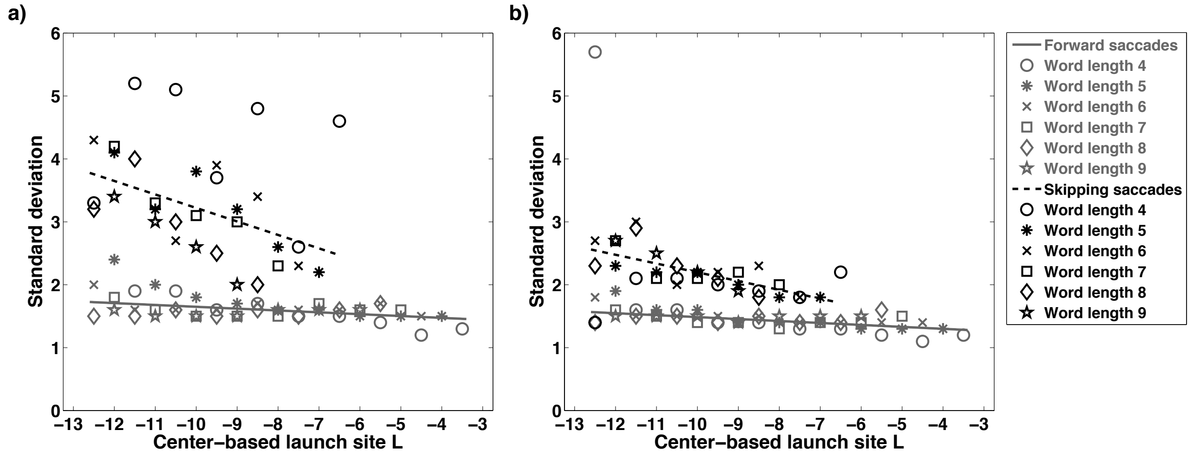

Figure 2.3. Standard deviations of landing-position distributions for words of different length in simple forward saccades and skipping saccades as a function of center-based launch site. (a) Estimated standard deviations of uncorrected distributions for different launch-sites, word lengths, and saccade-types. (b) Estimated standard deviations for error-corrected distributions without mislocated fixations.

Another important result of the correction concerns the particular large variability of the estimates for both mean and standard deviations of uncorrected landing distributions in skipping saccades (Figures 2.2a and 2.3a). After correction for mislocated fixations, this variability was reduced substantially and goodness-of-fit measures for simple linear regression analyses in skipping saccades (R^2=0.51 for landing-position function, Figure 2.2b) turned out to be comparable to corresponding values for simple forward saccades (R^2=0.37, Figure 2.2b).

2.4.3 Intended fixation probabilities

As discussed in the beginning of Section 2.4, the correction of experimental data for mislocated fixations requires the simultaneous adjustment of landing-position distributions and the target-selection probabilities of upcoming words. Here, we improved the original estimation procedure developed by Engbert and Nuthmann (2008) by computing results separately for simple forward saccades and skipping saccades. As a result, our estimates of intended skipping probabilities differ slightly from the predictions based on the previous version of the model. We reproduced Engbert and Nuthmann's (2008) finding that failed skippings (i.e., undershoot errors) are much more frequent than unintended skippings (i.e., overshoot errors, see Figure 2.4).

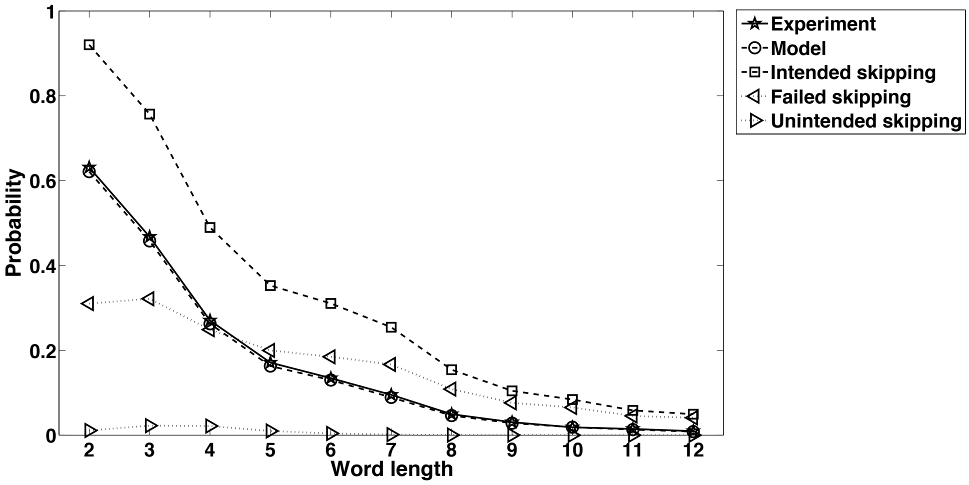

Figure 2.4. Skipping probabilities for 2–12-letter words under the influence of oculomotor errors. Mislocated fixations generate deviations between intended (squares, dashed line) and simulated (circles, dashed line) fixation probabilities for word skipping which match experimentally observed skipping probabilities (stars, solid line). While overshoot errors are negligible (right-pointing triangle, dotted line), undershoot errors are very likely (left-pointing triangle, dotted line).

The most important difference, however, concerns intended skipping probabilities for word lengths shorter than 5 characters, for which the improved algorithm predicts much higher intended skipping rates (Figure 2.4, squares, dashed line) than suggested by Engbert and Nuthmann's (2008) results. For short words, we find intended skipping rates up to more than 90% (for 2-letter words), i.e., the oculomotor model predicts that readers almost always attempted to skip 2-letter words, however, oculomotor errors very frequently (more than 30% in 2-letter words) prevented the skipping due to undershoot (left-pointing triangles, dotted line).

2.5 Discussion

Within-word landing positions during reading are modulated by word length and launch-site distance. A traditional description of this effect is based on the concept of the saccadic range error (McConkie et al., 1988), a systematic tendency for undershoot of a far saccade target and overshoot of a near target. The aim of the present study was to investigate the limits of such an explanation based on an analysis of word skipping during continuous reading. In this attempt, differences in the launch-site effect between skipping and non-skipping saccades represent inconsistencies with the range-error explanation, since it is only the distance between launch site and target word that is relevant to the range-error model of the launch-site effect. Generally, we replicated differences in the launch-site effect observed by Radach (1996; see also Radach & McConkie, 1998; Radach & Kempe, 1993). First, we found remarkable differences between skipping saccades and normal forward saccades. In particular, we observed an increased launch-site effect for skipping saccades, i.e., the general leftward shift of the mean landing position with increasing launch-site distance is more pronounced for skipping saccades compared to non-skipping saccades. Second, our analysis demonstrated increased standard deviations for landing-position distributions after skipping saccades compared to non-skipping saccades.

Before we interpreted our results, we addressed an important drawback of the analysis of within-word landing-position distributions. A substantial proportion (about 15% - 20%) of all saccades land on unintended target words and, therefore, represent mislocated fixations (Nuthmann et al., 2005). Following McConkie et al.'s (1988) suggestion and recent computational techniques for the estimation of mislocated fixations from experimental data (Engbert & Nuthmann, 2008), we corrected our data for the effect of mislocated fixations and demonstrated the reliability of the differences in the launch-site effect between skipping and non-skipping saccades. As a remarkable finding, we observed that the launch-site distance has a very little effect on the random placement error for non-skipping saccades. This result underlines our earlier speculation that the size of saccadic errors observed in word targeting during reading is hardly limited by the performance of the oculomotor system, since single responses to point targets produce a negligible oculomotor error (Kapoula, 1985).

What are possible theoretical explanations for the increased launch-site effect in skipping saccades? First, Vitu (1991a; see also Vitu et al., 2006; Vitu, 2008) postulated a *center-of-gravity effect* (CoG) in saccade preparation as an explanation for the launch-site effect. In this model, the spatial configuration of word objects is responsible for any systematic deviation from the saccade target (e.g., word center). Because the spatial layout is substantially different for skipping and non-skipping saccades, the CoG effect is a candidate for an explanation of the current findings. However, quantitative predictions are currently not available, because the CoG model was not formulated in mathematical detail so far. Nevertheless, the CoG effect might be relevant to the phenomenon.

Second, Radach (1996) proposed that the increased launch-site effect in word skipping is caused by a strategical effect, so that “saccades may sometimes be aimed at units of two words in which case a small function word is not ‘skipped’ but remains unfixated because it is part of the larger two-word target unit” (Radach & McConkie, 1998, p. 83). While such an explanation clearly represents an alternative explanation of the effect, quantitative predictions are necessary to explore whether the strategy shift model is consistent with both within-word landing-position distributions and fixation probabilities (e.g., skipping probability, refixation probability), which might be difficult to square with experimental data. Interestingly, the concept of mislocated fixations would play a completely different role, if two-word targets must be taken into account. Thus, we believe that Radach’s (1996) hypothesis needs to be explored quantitatively in future research.

Third, Morrison (1984) suggested that in case of word skipping a compromise landing position in between words *N+1* and *N+2* might result from interfering saccade-planning processes to each of both words. Morrison assumed that if attention is shifted from word *N+1* to word *N+2* after “amplitude computation for the first one is always underway; then the saccade will be directed partly to the location of the first word and partly to the second.” (Morrison, 1984, p. 680). As a consequence, this model could also qualitatively account for an increased leftward shift of landing distributions after word skipping.

Fourth, a new theoretical model of the launch-site effect based on Bayesian estimation of the saccade target was proposed recently (Engbert & Krügel, 2010). According to this model, saccade targets are computed from the product of the likelihood of the observation (i.e., the conditional probability $p(x|x_0)$ of a target at position x given an observation of the target at position x_0) and the prior distribution $p(x)$ representing our previous knowledge on all realized target distances. However, in the Bayesian model, different prior distributions and/or likelihood functions would necessarily be needed as an assumption to explain the differences of the launch-site effect between skipping and non-skipping saccades. Thus, new experimental work on the Bayesian model must be carried out as a next step in the verification of this hypothesis.

Fifth, while our results suggest that the saccadic range error cannot explain the difference of the launch-site effect between skipping and non-skipping saccades, it might still play a subordinate role in producing the overall effect. A combination of multiple processes of the list of candidates discussed here seems to be highly plausible.

In conclusion, we believe that the investigation of the launch-site effect in reading will develop into a productive research program, both experimentally and theoretically, and will provide important boundary conditions for computational models of eye-movement control (e.g., Engbert et al., 2005; Reichle et al., 2009; for an overview see Reichle et al., 2003).

2.6 Appendix

Launch	4-letter Words				5-letter Words				6-letter Words				7-letter Words				8-letter Words				9-letter Words			
Site	Mean	SD	Res	N	Mean	SD	Res	N	Mean	SD	Res	N	Mean	SD	Res	N	Mean	SD	Res	N	Mean	SD	Res	N
-5	3.0	1.4	0.001	2588	3.1	1.6	0.003	1477	3.3	1.6	0.004	1331	3.4	1.6	0.009	1015	3.7	1.6	0.009	1028	4.0	1.5	0.008	1142
-6	2.8	1.5	0.004	2044	2.9	1.6	0.006	2320	3.1	1.7	0.003	1893	3.2	1.5	0.008	1468	3.5	1.5	0.007	1498	3.8	1.5	0.007	1454
-7	2.4	1.7	0.003	1376	2.6	1.7	0.006	1477	2.8	1.6	0.007	1331	2.9	1.5	0.007	1015	3.1	1.6	0.006	1028	3.6	1.5	0.006	1142
-8	2.1	1.6	0.001	758	2.5	1.8	0.003	871	2.7	1.6	0.004	789	2.7	1.6	0.005	697	3.1	1.5	0.008	657	3.2	1.6	0.007	778
-9	1.9	1.9	0.003	332	2.1	2.0	0.004	467	2.5	1.6	0.008	363	2.7	1.8	0.003	427	2.6	1.5	0.011	326	3.0	1.6	0.006	455
-10	1.7	1.9	0.001	121	1.8	2.4	0.004	202	1.8	2.0	0.005	221	2.7	1.9	0.008	207	2.8	1.9	0.008	150	3.1	1.6	0.012	278
-11	-1.3	6.0	0.017	40	2.3	2.0	0.009	119	1.6	1.9	0.015	96	2.3	2.0	0.004	85	2.4	1.9	0.019	65	2.4	2.1	0.010	180
-12	2.4	1.1	0.012	21	1.8	2.2	0.006	52	-3.5	4.4	0.007	46	2.6	1.6	0.020	37	3.5	2.0	0.040	10	2.5	1.9	0.013	103

Table 2.1. Means and standard deviations of landing position distributions fitted to the normal curve in simple forward saccades. Launch site is indicated with negative numbers reflecting the number of letter positions to the first letter of the target word. Each value in the Mean column is the estimated mean of the within word landing position distribution. Negative values indicate distributional means that are located to the left of the space before target words. Each value in the Res column is the average of the absolute values of the residuals for the data points in the landing position distribution. Each value in the N column is the number of observations for a given distribution.

Launch	4-letter Words				5-letter Words				6-letter Words				7-letter Words				8-letter Words				9-letter Words			
Site	Mean	SD	Res	N	Mean	SD	Res	N	Mean	SD	Res	N	Mean	SD	Res	N	Mean	SD	Res	N	Mean	SD	Res	N
-5	-3.8	4.6	0.002	231	1.3	2.2	0.006	224	2.2	2.3	0.006	184	1.7	2.3	0.006	159	2.7	2.0	0.007	144	3.1	2.0	0.011	84
-6	0.7	2.6	0.001	697	0.6	2.6	0.004	672	-0.3	3.4	0.008	532	0.0	3.0	0.005	671	1.5	2.5	0.007	425	2.0	2.6	0.012	255
-7	-6.4	4.8	0.001	977	-0.9	3.2	0.001	1007	-3.0	3.9	0.002	777	-0.8	3.1	0.003	756	-0.5	3.0	0.003	551	1.3	3.0	0.009	364
-8	-2.9	3.7	0.002	995	-3.1	3.8	0.001	1085	-0.3	2.7	0.004	885	-1.9	3.3	0.004	791	-2.8	4.0	0.005	535	0.8	3.4	0.008	392
-9	-7.0	5.1	0.002	950	-1.1	3.1	0.002	834	-10.0	5.8	0.005	727	-4.6	4.2	0.003	621	-0.6	3.2	0.005	515	-2.7	4.3	0.012	370
-10	-9.9	5.2	0.003	725	-2.8	4.1	0.002	838	-4.8	4.3	0.003	526	0.3	2.4	0.004	490	-1.6	3.7	0.005	426	-0.1	3.2	0.007	334
-11	-2.9	3.5	0.006	506	-2.5	3.8	0.006	744	0.1	2.9	0.004	417	-2.3	3.4	0.007	397	1.2	2.6	0.006	352	-0.2	2.8	0.008	290
-12	-0.8	3.1	0.003	366	-1.2	3.2	0.004	485	-5.0	4.4	0.003	345	-0.3	2.8	0.002	307	-1.7	3.9	0.008	307	-1.2	3.8	0.016	202

Table 2.2. Means and standard deviations of landing position distributions fitted to the normal curve in skipping saccades. Launch site is indicated with negative numbers reflecting the number of letter positions to the first letter of the target word. Each value in the Mean column is the estimated mean of the within word landing position distribution. Negative values indicate distributional means that are located to the left of the space before target words. Each value in the Res column is the average of the absolute values of the residuals for the data points in the landing position distribution. Each value in the N column is the number of observations for a given distribution.

3. Fixation positions after skipping saccades: A single space makes a large difference

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Abstract. During reading, saccadic eye movements are generated to shift words into the center of the visual field for lexical processing. Recently, Krügel and Engbert (2010, see chapter 2) demonstrated that within-word fixation positions are largely shifted to the left after skipped words. However, explanations on the origin of this effect cannot be drawn from normal reading data alone. Here we show that the large effect of skipped words on the distribution of within-word fixation positions is primarily based on rather subtle differences of the low-level visual information acquired before saccades. Using arrangements of x-letter strings, we reproduced the effect of skipped character strings in a highly controlled single-saccade task. Our results demonstrate that the effect of skipped words in reading is the signature of a general visuo-motor phenomenon. Moreover, our findings extend beyond the scope of the widely accepted range-error model, which posits that within-word fixation positions in reading depend solely on the distance of target words. We expect that our results provide critical boundary conditions for the development of visuo-motor models of saccade planning during reading.

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3.1 Introduction

When we read a line of text our eyes initially skip over up to 1/3 of all words during first pass (Rayner, 1998). Much attention has been paid to the factors that influence on a reader's decision to skip the next word. Independent effects of the length, the predictability, and the frequency of the next word have been identified as important for the cognitive decision to trigger a word skipping (Brysbaert, Drieghe, & Vitu, 2005; Drieghe, Desmet, & Brysbaert, 2007; Rayner, & McConkie, 1976; Rayner et al., 1996; Rayner, Slattery, Drieghe, & Liversedge, 2011; Rayner & Well, 1996; Vitu, O'Regan, Inhoff, & Topolski, 1995). However, word length turned out to be the most important variable determining word skipping. Short words are more frequently skipped than long words (and so are high-predictability words and high-frequency words when word length is controlled for). Here, we focus on the analysis of average landing positions after normal (i.e., from word N to word N+1) and skipping saccades (from word N to word N+2).

Where the eyes land within words is primarily determined by low-level visuo-motor variables such as inter-word spaces or the distance and the length of target words (Rayner, 1998). Most importantly, average landing positions of saccades vary systematically as a function of the prior distance of the eyes (i.e., the launch-site distance) from the target word (McConkie et al., 1988). Each one-letter increment of the launch-site distance shifts the distribution of subsequent fixation locations within the next word about half a letter to the left. This well-established finding is often interpreted as a signature of a saccadic range error (Kapoula, 1985) during reading (McConkie et al., 1988). As a result, average first-fixation positions at word centers without systematic under- or overshoot (McConkie et al., 1988; O'Regan, 1981; O'Regan & Levy-Schoen, 1987; Rayner et al., 1996; Vitu et al., 1990) are realized only from specific launch-site distances.

In a recent study, Krügel and Engbert (2010, see chapter 2) demonstrated that word skipping is another important factor that influences saccade landing positions during reading (see also Radach, 1996; Radach & McConkie, 1998; Radach & Kempe, 1993). Using a large corpus of eye-movement data Krügel and Engbert (2010, see chapter 2) ran separate analyses for normal and skipping saccades for identical launch-site distances. As a result, landing positions could be decomposed by saccade type. Word skipping strongly modulated the launch-site effect by inducing a large additional leftward shift of the average initial fixation position within the target words. By such an extra leftward displacement of two or more

letters (depending on the launch-site distance), the effect of skipped words turned out to be as large as the effect of an approximately six or seven letters increment of launch-site distance.
The present study was motivated by two questions related to the work by Krügel and Engbert (2010, see chapter 2). First, it is unclear whether the relocation of saccadic end points in word skipping reflects a strategic effect under top-down control or whether it is due to low-level visuo-motor constraints. Radach and McConkie (1998) hypothesized that in some cases readers might aim at an intermediate position between the skipped word and the word after the skipped word to keep the skipped word in close foveal distance for further word processing (see also Radach, 1996). If this is the main cause of the effect of word skipping on landing positions in reading, then we can expect that the effect is limited to normal reading conditions. On the other hand, if the effect is a signature of a general visuo-motor phenomenon it should also be present under conditions in which a final eye-position near the skipped word provides no processing benefits.

Second, in reading it is difficult to know which word is the target of a given saccade. It is evident from overlapping within-word landing-position distributions that a substantial proportion (about 15–20%) of all saccades miss their target words and result in mislocated fixations on unintended word neighbors (McConkie et al., 1988; Engbert & Nuthmann, 2008). As a consequence, Krügel and Engbert's (2010, see chapter 2) analyses were based on advanced statistical techniques (Engbert & Nuthmann, 2008; see also Nuthmann et al., 2005) to estimate unbiased probability distributions for landing positions within target words of intended skipping saccades and intended normal saccades. Such a procedure can be avoided in single-saccade paradigms.

Therefore, we developed a single-saccade task with a clear target word both in skipping and normal saccades and with tight experimental control of launch-site distance, word length, and size of the skipped word. We used meaningless arrangements of x-letter strings to eliminate lexical processing of the skipped word in order to establish the potentially visuo-motor nature of the effect.

3.2 Method

3.2.1 Participants

30 students at the University of Potsdam (22 female, 8 male), aged between 19 and 44 years, received study credit or a total of 21 € for participating in three 45 to 60-minutes sessions;

they were all naïve with respect to the purpose of the experiment. All of the participants reported normal or corrected-to-normal vision.

3.2.2 Apparatus

With their heads supported on a chin rest, participants were seated at a viewing distance of 60 cm in front of a 22-in. FT/LCD monitor (refresh rate: 60 Hz; resolution: 1,680 × 1,050 pixels). Stimuli were presented in fixed-width Courier font with a size of 18 points on the vertical centerline of the computer display. Eye movements were recorded binocularly using an EyeLink II system (SR Research, Osgoode/Ontario, Canada) with a sampling rate of 500 Hz and a spatial resolution better than 0.01°.

3.2.3 Material

The stimulus display consisted of two groups of items: an arrangement of x-letter strings of variable length followed by three German nouns. Drawn randomly from a pool of 3,888 different nouns, with an equal number of high- and low-frequency words, 1296 unique word triplets were generated separately for each participant. They were split equally into three subsets of 432 triplets, defined by the length of the first word. The first noun was a 4-, 6-, or 8-letter word, the second was a 7-letter word, and the third word had 9, 7, or 5 letters, respectively (all three word lengths summed up to 20 letters). On 48 randomly selected triplets in each subset, one word was replaced by an animal name of the same length, resulting in a total of 144 positive animal-name trials (approx. 11% of all trials). The position of this animal name within the group of three words was balanced across all selected triplets. The x-letter string was presented so that the subjects' initial fixation positions were always located at the third x. From this starting position the string of xs extended 4, 6, 8 or 10 letters to the right, resulting in varying initial launch-site distances of the eyes to the space before the first noun of -5, -7, -9, or -11 character positions, respectively[5]. In 50% of the trials, the foveal string of x letters was split into two parts by replacing one of the xs by a space; thus, the initial saccade to the first, target word of the triplet required the skipping of the second part of the string. Nested within four conditions of different launch-site distance, the space within the x-letter string appeared equally likely at one to four different positions leading to up to four

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[5] Note that we did not test for launch-site distances of -4 letters to the left of the beginning of the target word which is the minimally required launch-site distance to skip over two-letter words in spaced texts. Two letter words are the shortest words in German.

different lengths of the second part of the x-letter string (see Figure 3.1, dashed boxes). In 50% of the skipping saccade trials, the second part of the x-letter string started with an uppercase x. All factors were counterbalanced within and across the three experimental sessions and presented in random order.

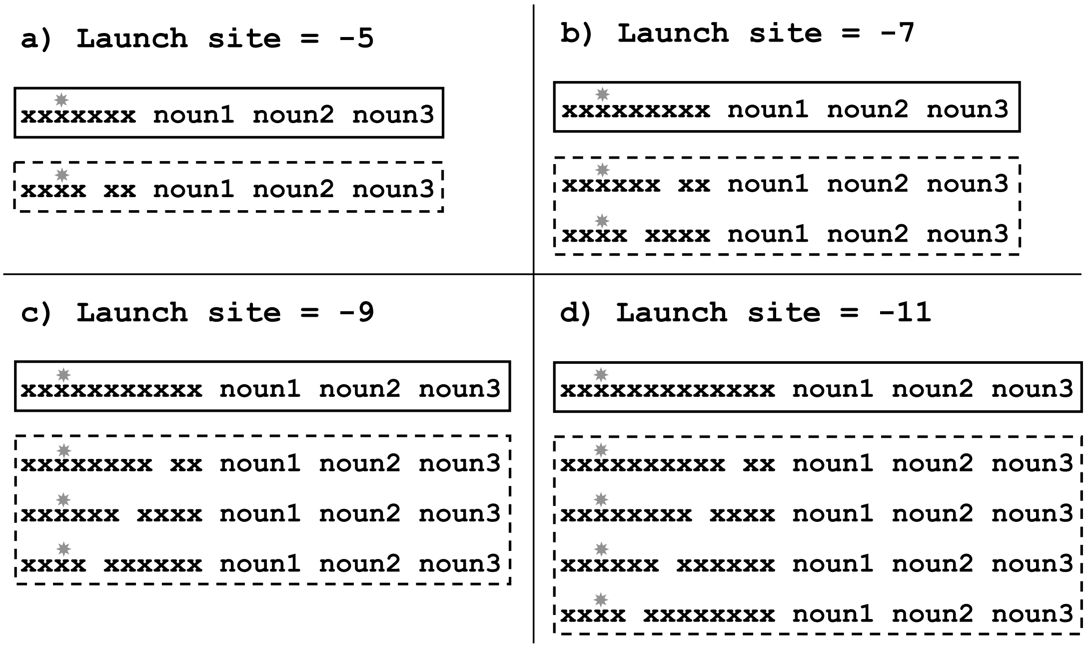

Figure 3.1. Visual configuration of the stimulus material. A group of three nouns follows an arrangement of x-letter strings. The presence or absence of the space in the x-letter configuration distinguishes skipping saccade (dashed boxes) from normal saccades (solid boxes) to noun1.

3.2.4 Procedure and Design

For each participant the experiment was composed of three sessions that were conducted on three different days. At the beginning of each session the participants were introduced to the task in a 12-trial practice block; actual testing occurred in four subsequent test blocks with 108 trials per block. Participants were instructed to read a list of three German nouns to determine if one of the words was the name of an animal and to respond by key press without making any errors. They were further told to ignore the string(s) of x letters and were instructed to move their eyes directly to the first word of the word triplet. Each trial began with the presentation of a “Ready” signal centrally on a plain white screen, which was replaced after 1 sec by a fixation cross at the left of the screen. Both the offset of the fixation cross and the simultaneous onset of the stimulus presentation were then triggered by the participants’ fixation in a predefined area around the fixation cross. The stimulus display remained in view until a response key was pressed. Participants received auditory feedback after each trial (low tone = correct, high tone = incorrect). Finally, all participants were informed about their total performance after every block.

3.2.5 Data Selection

Initial saccades after stimulus onset were analyzed. Trials with eye blinks were excluded from analyses.

3.3 Results

We were interested in systematic shifts of saccade landing positions for normal, one-word saccades vs. skipping saccades. Figure 3.2 presents the comparison of overall landing-site distributions observed after normal saccades and skipping saccades for launch-site distances of -5, -7, -9, and -11 letters from the left boundary of the target word[6]. All distributions of first fixation positions were fitted by normal distributions (i.e., the lines in Figure 3.2). The effect of saccade type (normal vs. skipping) turned out to be significant (paired sample t-test comparisons of the mean landing sites in the four different launch site conditions all demonstrated $p < 0.001$). Therefore, we reproduced the main effect of the normal vs. skipping saccades on the distribution of saccade landing sites (Krügel & Engbert, 2010, see chapter 2) in a highly controlled single-saccade task.

We did not obtain reliable differences in landing-site distributions for different lengths of the target words, which is different from findings in normal reading (e.g., McConkie et al., 1988). Separate repeated-measure one-way ANOVAs with word length as the factor of variation were carried out for all combinations of launch site distance and saccade type. In 3 out of 8 tests (launch site -7 and -9 in simple saccades; launch site -7 in skipping saccades) we found significant effects of word length with $p<0.01$. However, these effects refer to actual differences of the mean landing positions with a maximum of less than 0.3 character spaces. Thus, we used aggregated data across target-word lengths for all further analyses.

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[6] Estimates of landing-site distributions in natural reading are typically based on observations that are truncated at word boundaries (see Engbert & Nuthmann, 2008, for a technical discussion). The results reported here would still be valid if all calculations were carried out using Gaussian fits of landing-position distributions from data restricted to landing positions within the target words.

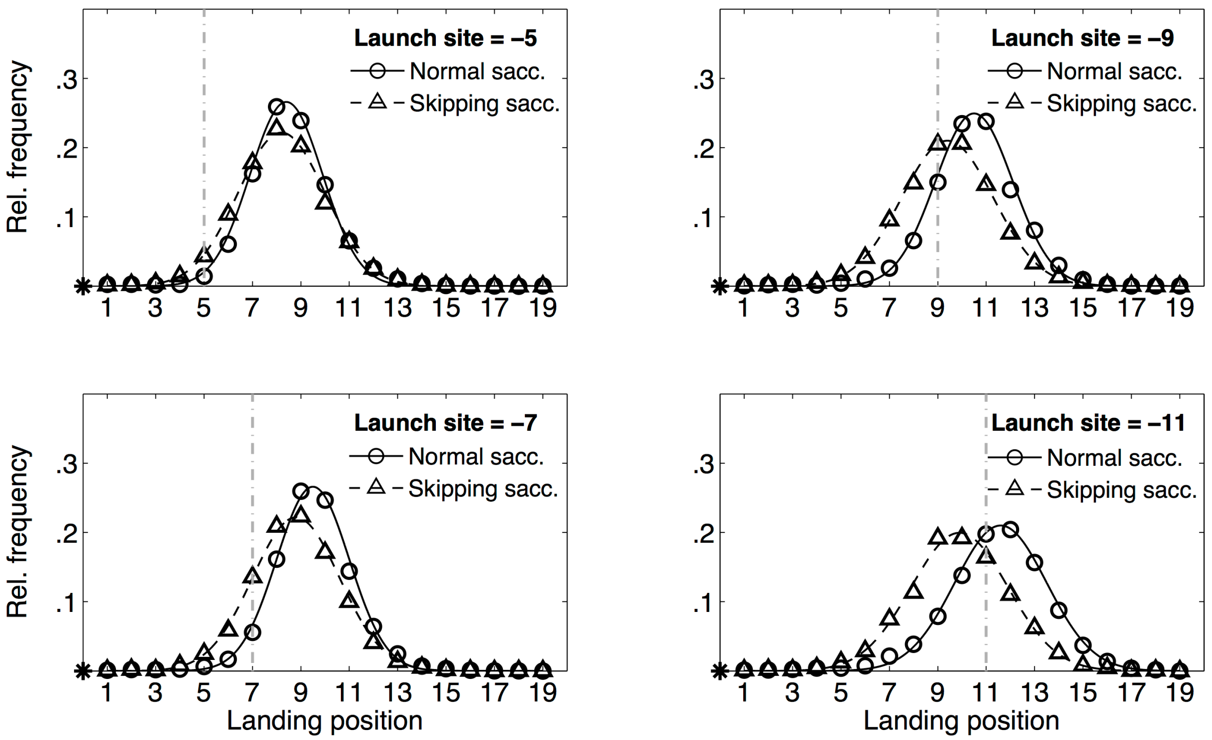

Figure 3.2. Distributions of landing positions in normal, one-word saccades (circles, solid lines) and in skipping saccades (triangles, dashed lines) for launch-site distances of -5, -7, -9 and -11 letters to the left of the space before the first noun. Asterisks on the horizontal line denote saccades' launch sites and numbers on the horizontal line indicate letter positions to the right of saccades' launch sites. The vertical dashed grey lines mark the position of the space before of the first letter of the target word.

Next, we investigated systematic interactions between the main factors, i.e. launch-site distance and saccade type. Figure 3.3 presents estimated means of the landing site distributions and associated linear regression lines for normal saccades (circles, solid line) and skipping saccades (squares, dashed line) as a function of launch-site distances. Repeated-measure two-way ANOVA demonstrated large main effects of launch-site distance (F(3,36862)=2475.81 p<0.001) and saccade type (F(1,36862)=2229.99 p<0.001) and a significant interaction (F(3,36862)=164.58, p<0.001). With increasing launch-site distance, mean landing positions were systematically shifted by factors of 0.5 letters in simple saccades and 0.7 letters in skipping saccades towards the beginning of target words. It is obvious from Figure 3.3 that the effect of skipped x-letter strings turned out to be marginal for the shortest launch site condition but increased up to a leftward displacement of 1.8 letters compared to simple saccades for launch-site distances of -11 letters. Based on the skipping of meaningless word-shaped objects, these findings qualitatively replicate the main results reported by Krügel and Engbert (2010, see chapter 2) for normal reading. Further analyses on effects of the position of the space within the x-letter string are provided as Supplemental Information (see

Section 3.5). Taken together, we conclude that the landing-position effect after skipped words is not restricted to normal reading, but might represent a robust visuo-motor phenomenon.

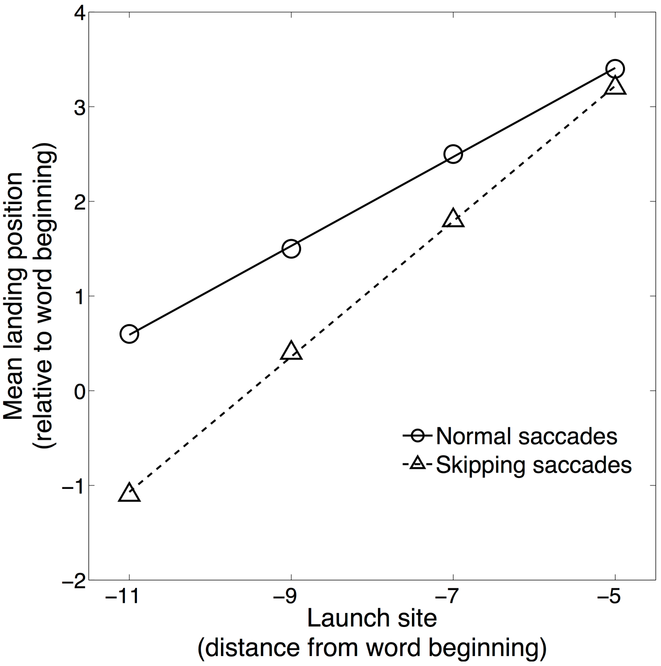

Figure 3.3. Initial mean landing positions as a function of launch-site distances from word beginning for simple saccades (circles, solid line) and skipping saccades (triangles, dashed line). Linear regressions indicate pronounced difference in both slope and intercept of the relations for the two conditions.

3.4 Discussion

The primary goal of the present study was to test the effect of word skipping on fixation position under highly controlled constraints in a single saccade paradigm. Using arrangements of x-letter strings, which were placed before a task-relevant group of three words, we qualitatively replicated the substantial left-shift of landing positions after skipping saccades, demonstrated by Krügel and Engbert (2010, see chapter 2) for normal reading. In particular, we found a strong interaction between the two main effects of launch site distance and saccade type (i.e., normal vs. skipping saccade).

On a quantitative level, we obtained some differences compared to the findings by Krügel and Engbert (2010, see chapter 2). First, the systematic launch-site contingent shift of mean landing sites in the present experiment appeared to be larger than in natural reading in both normal and skipping saccades. In contrast to the present estimated regression slopes of 0.53 (normal saccades) and 0.72 (skipping saccades), Krügel and Engbert (2010, see chapter 2) reported estimates of 0.27 for normal saccades and 0.48 for skipping saccades for normal reading. Second, with a maximum effect size of 1.8 letters the effect of skipped letter strings in the present experiment appeared to be smaller than in reading. Furthermore, we found little effect of the length of the target word. In a recent work, Engbert and Krügel (2010) demonstrated that readers use task-specific prior knowledge about the probability distribution of target distances for optimal target localization based on Bayesian saccade planning. According to such a model, the restricted range of particularly long target distances in the current experiment might have created the quantitative differences in comparison to reading. The range of long target word distances used in the present experiment may also explain why we did not observe effects of the length of target words, since the position of the right boundary of target words in the present experiment fell most frequently outside the perceptual span of approximately 14-15 letters to the right of the current fixation position (DenBuurman, Boersma & Gerrissen, 1981; McConkie & Rayner, 1975; Rayner, 1986). Thus, visual information about the length of target words was nearly absent in most of the trials.

Multiple studies on saccadic eye movements indicated that the distance between saccades' launch sites and target words systematically influences the mean fixation location in words in reading (McConkie et al., 1988; Nuthmann et al., 2005; Rayner et al., 1996; Reilly & O'Regan, 1998). The demonstration that this effect varies for normal vs. skipping saccades is very important, because the phenomenon cannot be explained by current models of saccade generation. Both range-error (Kapoula, 1985; McConkie et al., 1988) as well as Bayesian estimation of the target position (Engbert & Krügel, 2010) are based on launch-site distance and word length as unique predictors of within-word landing position. The effect may potentially be accounted for by an alternative model based on the global effect (Deubel et al., 1984; Findlay, 1982; Vitu, 2008), although it is still not certain as this model has not been elaborated to deliver quantitative predictions. A combination of multiple oculomotor mechanisms (range error, global effect, Bayesian estimation of target positions) working in parallel is also possible. Thus, the current results are challenging to future modeling attempts. Since the presence of an additional single space in skipping saccades and its position relative to the beginning of the target word (see Supplement Figure 3.4) makes a large difference on saccades' landing sites, new oculomotor models need to include explicit representations of the positions of spaces within the reading material in addition to other well-known low-level determinants like target-word distance and target-word length.

Our results contradict an earlier hypothesis that the shift of the eye's landing sites towards the beginning of words in word-skipping saccades might reflect occasionally top-down control with the function to keep the skipped word in close foveal distance for further word processing after the skipping saccade (Radach, 1996; Radach & McConkie, 1998). In the present experiment, the final eye position in skipping saccades was relocated near the task-irrelevant skipped string of xs; indeed subjects were asked to identify animal names within the group of three words to the right of the x-letter arrangement. Thus, the observed effect of skipped letter-strings indicates automatic oculomotor mechanisms. However, our results do not exclude that this automatic low-level oculomotor mechanism serves further linguistic processing of the skipped word in normal reading.

Implications of the effect of skipping saccades on fixation position are important for theoretical models of eye guidance in reading. To account for the distribution of fixation positions within words, current models of eye-movement control in reading (e.g., Engbert et al., 2005; Reichle, Rayner, & Pollatsek, 1999) typically incorporate the launch-site contingent mean shift of saccadic landing positions within words based on McConkie et al.'s (1988) quantitative estimates. However, the new observation of the effect of word skipping uncovers that McConkie et al.'s (1988) important findings are strongly biased by mixing up two more fundamental populations of saccades, namely normal and skipping saccades. In effect, current reading models largely overestimate the accuracy of skipping saccades and, even more importantly, underestimate the accuracy of simple progressive saccades to words *N+1*.

In conclusion, we believe that our results set important boundary conditions for the development of visuo-motor models of saccade planning during reading and, at a more general level, for computational models of eye-movement control.

3.5 Supplementary information

When normal saccades (i.e., from word *N* to *N+1*) and skipping saccades (i.e., from word *N* to *N+2*) are launched from equal distances towards target words, the space at the end of the current word *N* constitutes the most obvious low-level visual difference. In normal, one-word saccades, this space is always located one character position in front of the target word; hence the launch-site word *N* constitutes a continuous letter-string up to the beginning of the target word. In skipping saccades, however, the space at the end of word *N* is located before the intermediate and skipped word *N+1* and therefore, interrupts the string of letters in-between the current fixation position and the beginning of the target word at varying positions depending on the length of the skipped word *N+1*. Here we test how saccadic landing sites depend on the position of the space at the end of the foveal x-letter string (i.e., the launch site string).

In Figure 3.4, saccades' mean landing positions relative to the beginning of the target words are plotted as a function of the position of the space after the launch-site x-letter string. Position zero on both the horizontal and the vertical axis denotes the position of the space before the target word. Positive numbers refer to the letters within the target word, negative numbers on both axis reflect character positions left-hand of the space before the target word. Different symbols and curves separate the data contingent on the different launch-site distances within the experiment. The vertical differences across these curves reflect the main effect of the four different launch-site distances realized within the present experiment.

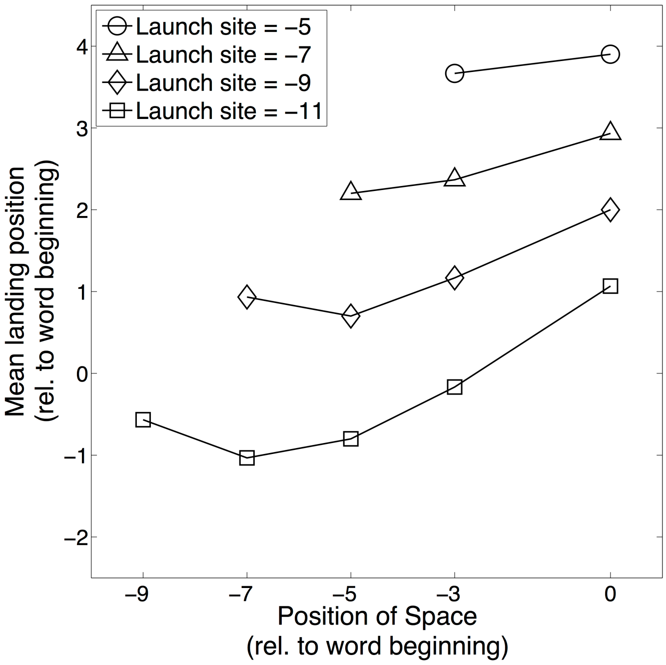

Figure 3.4. Initial mean landing positions as a function of the position of the first space after the launch site.

Interestingly, saccadic landing sites vary systematically as a function of the position of the space at the end of the launch-site string. Normal saccades (data points at the zero-horizontal location) are instances in which the space is located immediately before the first letter of the target word; their mean landing positions is further into the word compared to the mean landing position of skipping saccades. In fact, when the space moves away from the target word, and the length of the intermediate letter string increases, landing sites systematically shift in the corresponding leftward direction, leading to a very gradual transition from landing positions in simple saccades to landing positions in skipping saccades. Still, this trend comes to a stop or even reverses when the space at the end of the launch-site string approaches the current fixation position and the intervening word is very long.

Thus, the position of the first space to the right of the current fixation position turns out to be an important determinant of saccadic end points, and may play a dominant role in the process of saccade planning. In general, this finding is highly compatible with an observation by Pollatsek and Rayner (1982) who demonstrated that the first space to the right of the current fixation "is the primary space information used by readers of English" (Rayner & Pollatsek, 1996, p. 463). In their study, the reading rate of English texts was slowed by 40% to 60%, if space information was removed. However, when only the space between words *N* and words *N+1* was preserved, the reading rate recovered to a level of 90% of the reading rate in ordinary spaced texts.

As the effect of the position of the first space to the right of the current fixation position probably underlies the effect of word skipping on initial landing sites in words, it will be worth investigating further in future studies.

4. A model of saccadic landing-positions in reading under the influence of sensory noise

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Abstract. During reading, saccadic eye-movements are produced to move the high acuity foveal region of the eye to words of interest for efficient word processing. Distributions of saccadic landing-positions peak close to a word's center but are relatively broad compared to simple oculomotor tasks. Moreover, landing-position distributions are modulated both by distance of the launch site and by saccade type (e.g., one-step saccade, word skipping, refixation). Here we present a mathematical model for the computation of a saccade intended for a given target word. Two fundamental assumptions are related to (i) the sensory computation of the word center from inter-word spaces and (ii) the integration of sensory information and a-priori knowledge using Bayesian estimation. Our model was developed for data from a large corpus of eye movements from normal reading. We demonstrate that the model is able to simultaneously account for a systematic shift of saccadic mean landing position with increasing launch-site distance and for qualitative differences between one-step saccades (i.e., from a given word to the next word) and word-skipping saccades.

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4.1 Introduction

Most theoretical models of eye-movement control during reading agree on that readers move their eyes on a word-based trajectory with word centers serving as functional target locations (e.g., Engbert et al., 2005; O'Regan, 1992; O'Regan, & Lévy-Schoen, 1987; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle et al., 2003; Reilly & Radach, 2006; but see Vitu, 2003, 2008, for an alternative framework). However, the question of “how this [functional target] location can be positively identified“ (McConkie et al., 1988, p. 1115) for the computation of a saccade is largely unresolved.

Word centers in printed texts lack any characteristic feature that could support its direct perceptual localization. Eye-movements experiments demonstrated that, even if colored letters highlighted word centers, saccadic landing positions were unchanged (Nuthmann, 2006). However, reading experiments with unspaced text (Spragins, Lefton, & Fisher, 1976) reported that the average reading rate was about half that of text with normal spacing. Epelboim, Booth, and Steinman (1994) argued that the most dramatic change when reading unspaced text was a rather modest reduction of the average saccade length and concluded that “Words, not spaces, may serve as the perceptual units that guide the line of sight through the text” (p. 1735). However, this conclusion was criticized in a reply by Rayner and Pollatsek (1996), who noted that removing spaces induced a remarkable increase in fixation duration. Moreover, in a subsequent work, Rayner and colleagues (Rayner, Fischer, & Pollatsek, 1998) investigated fixation durations and landing positions under spaced and unspaced reading conditions. They found that reading rates drop dramatically with removing spaces from the text as a result of shorter saccade amplitudes, larger fixation durations, and higher regression rates. Most importantly for the current work, Rayner and colleagues (1998) reported that within-word landing distributions with the typical pronounced peak near the word center (i.e., the *preferred viewing location* effect, Rayner, 1979) emerge only with spaces between words. In the various unspaced conditions of the experiments the authors consistently found highly left shifted landing distributions, which reveal a clear tendency to move towards the beginning of words. Another line of evidence for the specific role of word spaces to eye-movement control comes from gaze-contingent experiments by Pollatsek and Rayner (1982). In one of their experimental conditions, Pollatsek and Rayner (1982) experimentally filled the first space to the right (i.e., the space between the currently fixated word *N* and the next word *N*+1), which had a much stronger effect on fixation duration than filling the space between word *N*+1 and *N*+2. Rayner and Pollatsek (1996) concluded that “deprivation of space information causes subject to perform a more effortful calculation of where to go, but the eyes go more or less to the same place as when the space information is present" (p. 464). As a consequence, it is now widely assumed that readers rely on inter-word spaces for saccade planning during reading (Rayner, 1998).

Here we propose a mathematical model of saccade planning during reading, which (i) constructs an estimate of a target word's center from word boundaries as sensory input and (ii) feeds this estimate into a Bayesian approach to obtain an optimal estimate of the saccade target. We assume that the blank spaces between words are used as primary visual signals to derive spatial saccade-target coordinates close to the position of the word center. Before we develop our model in detail, we briefly review the two most important effects on within-word landing position: the effect of saccadic launch site and the effect of word skipping.

Launch-site distance.

When saccades need to be prepared, the distances to target-word centers change from saccade to saccade due to the variability of upcoming word lengths and due to seemingly erratic changes of launch sites (i.e., current within-word fixation positions). McConkie et al. (1988) discovered that the distances of target words from the launch sites of saccades strongly influence the landing positions. Their results showed that the *preferred viewing location* (Rayner, 1979) slightly left of the word center, i.e., the most likely average within-word fixation position, is due to a superposition of more fundamental launch-site contingent landing-position distributions. In particular, McConkie and colleagues (McConkie et al., 1988) found that the eyes systematically overshoot the center of words if saccades are launched from near fixation positions and systematically undershoot more distant word centers. When the launch-site distance was measured as distance from the target word center (center-based launch-site distance), the authors found an approximately linear relationship between the deviation from target word center and the center-based launch-site distance (see also Krügel & Engbert, 2010, see chapter 2; Nuthmann et al., 2005, Radach, & Kempe, 1993; Radach, & McConkie, 1998; Rayner et al., 1996). McConkie et al. (1988) concluded that the oculomotor system only partially compensates for the changes of launch-site distances from target words and, consequently, mean saccadic landing position is a function of the launch-site distance. More specifically, the estimated slope value of 0.5 for the linear regression model of average within-word landing position as a function of launch-site distance indicated that changes of the launch-site distance result in an adaptation of saccade amplitudes that compensate for approximately half its size: For each one-letter increment of the launch-site distance, mean saccadic landing position within words shifts half a letter to the left and for each one-letter decrement, mean landing position shifts half a letter to the right.

Word skipping.

When moving their eyes forward in a line of text, readers not only generate saccades from the currently fixated word *N* to the next word *N*+1 (one-step saccades), but also frequently decide to skip words, i.e., shift the gaze from word *N* to word *N*+2 (skipping saccades) or, occasionally, even to farther words *N*+*k* (*k*>2). In normal reading, roughly 1/3 of all words during reading are initially skipped (Rayner, 1998). Interestingly, within-word landing positions after skipping saccades differ from landing positions after one-step saccades - even if they are launched from the same distances to the target words. Krügel and Engbert (2010, see chapter 2) demonstrated that word skipping strongly modulates where the eyes land within the target word (see also Krügel, Vitu, & Engbert, 2012, see chapter 3; Radach & McConkie, 1998, Radach, 1996; Drieghe, Pollatsek, Staub, & Rayner, 2008). Figure 4.1 presents experimental data (Krügel & Engbert, 2010, see chapter 2) for the distributions of landing positions within words of different length for skipping saccades and one-step saccades, both launched from equal distances. The plots demonstrate largely left-shifted and broader landing-position distributions in skipping saccades than in one-step saccades. When readers skip a word, their eyes tend to land near the beginning of the target word - at an intermediate position between the skipped word and the target word.

In a more detailed analysis, Krügel and Engbert (2010, see chapter 2) provided separate plots and regression analyses for average within-word landing positions and the standard deviations of the corresponding landing-position distributions (see Figure 4.2), with each plot contingent on factors launch-site distance (in letters) and saccade type (one-step saccades vs. skipping saccades). For both measures (average landing position and standard deviation), a main effect of saccade type and an interaction of saccade type and launch-site distance was found. Saccades' average landing positions (Figure 4.2a) within words were generally shifted to the left after skipping saccades as indicated by an approximately 2-letter difference for the intercepts of the estimated regression lines in one-step saccades and skipping saccades. Additionally, the estimated slope values (0.27 in one-step saccades; 0.48 in skipping saccades) indicated that the average landing positions after skipping saccades exhibited a more pronounced leftward shift with increasing launch-site distances than the average landing positions after one-step saccades.

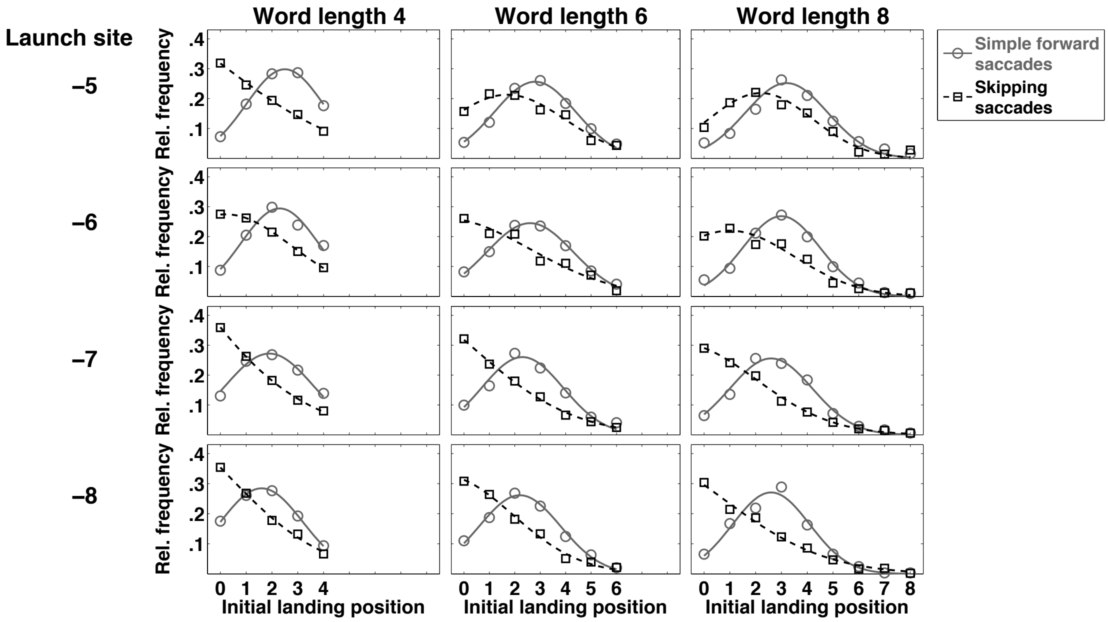

Figure 4.1. Initial landing-position distributions for words of lengths 4, 6, and 8 (columns) resulting from saccades, which were launched from –8 to –5 letters to the left of the beginning of the word (see panel rows). Landing-position distributions are decomposed into cases after skipping saccades (black) and one-step saccades (grey) (from Krügel & Engbert, 2010, see chapter 2).

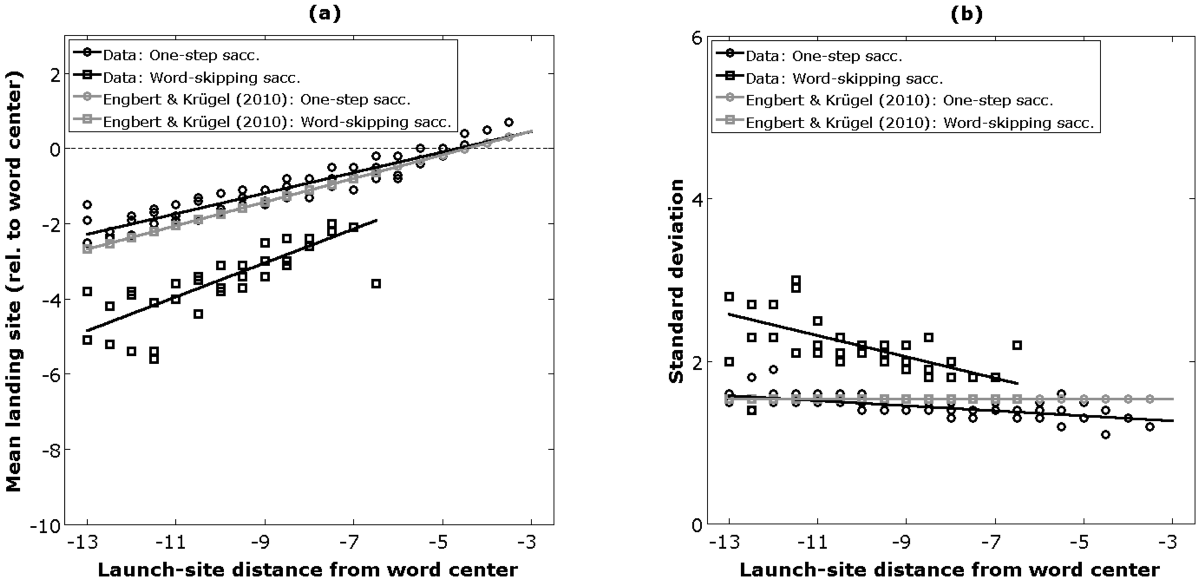

Figure 4.2. Plots of the launch-site effect as first proposed by McConkie et al. (1998). (a) Word-center based mean landing position as a function of saccadic launch-site distances to target-word centers. The zero value at the y-axis represents the word center (i.e., vanishing mean deviation). Positive values indicate overshoots of the word center and negative values undershoots. (b) Standard deviations of saccadic within-word landing-position distributions. Circles indicate resulting values for one-step saccades, while squares represent corresponding values for skipping saccades. Black symbols represent data from the reading experiment. Gray symbols show the corresponding fit of Engbert & Krügel (2010) model.

With respect to the random variability of saccadic landing positions (Figure 4.2b), Krügel and Engbert (2010, see chapter 2) observed that landing positions in skipping saccades are associated with a generally greater variability, confirmed by consistently larger standard deviations of the fitted normal distributions. Moreover, the standard deviations of the distributions of landing positions in word-skipping saccades markedly increased with increasing launch-site distances, whereas the standard deviations of the landing distributions in one-step saccades only slightly increased with longer target-word distances. It is important to note that this effect of skipping saccades on landing positions was recently qualitatively replicated for the skipping of meaningless letter-strings in a single-saccade experiment (Krügel et al., 2012, see chapter 3). This result was surprising and counter-intuitive, since left-shifted landing positions were detrimental for the task employed in the experimental paradigm. Therefore, a first conclusion for model development in this study is that the modulation of saccade amplitudes associated with the skipping of words during reading emerges from highly automatized low-level processes during saccade planning that are likely to be robust under variation of experimental details and independent of higher-level task-dependent goals.

Bayesian saccade planning during reading.

Human sensory coding of environmental stimuli is inevitably prone to error (Faisal et al., 2008; Knill & Pouget, 2004). Since sensory systems have no direct access to parameters in the environment, an optimal approach for sensory estimation is to maximize the conditional probability $p(x|x_o)$, i.e., the probability of a target at position x given a sensory estimate at position x_o. According to Bayesian decision theory (Berger, 1985; Jaynes, 1986), the conditional probability $p(x|x_o)$ is obtained as a posterior probability that can be computed as the product of the conditional probability $q(x_o|x)$ of the sensory evidence at position $x_o$given a target position at x, denoted as the likelihood, and a sensation-independent, prior probability $p(x)$ of saccade target positions,

$$p(x|x_o) = q(x_o|x)\, p(x), \qquad (4.1)$$

which is the general formulation of Bayes' rule applied to sensory-motor integration (Körding & Wolpert, 2004).

In recent work, Engbert and Krügel (2010) demonstrated that the saccadic launch-site dependence of within-word landing positions is a special case of the Bayesian principles, Eq. (4.1), for saccade planning in reading. In the mathematical model, the likelihood was modeled as an unbiased, normally distributed probability density, positioned at the center of the intended target word of the imminent saccade and with variance σ_o^2 reflecting the degree of sensory uncertainty. Assuming a Gaussian prior distribution of saccade target distances, the computation of the posterior probability density according to Bayes' rule simplifies to the product of two Gaussian densities, which results in another normal distribution. Most importantly, the resulting posterior probability gives a natural explanation of the launch-site effect, since the posterior distribution is shifted towards the maximum of the prior distribution (see Figure 4.3). As a result, the posterior estimate tends to overestimate the distance of the center of close target words and systematically underestimates the distance of far target locations. Comparing the model's predictions of landing positions (i.e., the posterior distributions) for a wide range of combinations of saccadic launch-site distances and target-word lengths with experimental data from a large corpus of eye-movement recordings during normal sentence reading, the authors demonstrated that the model accurately reproduced the systematic shift of mean landing positions with varying launch-site distances.

However, limitations of Engbert and Krügel's (2010) Bayesian model are twofold: First, the model does not include an algorithm for the computation of the word center from inter-word spaces. Second, lacking such a component, the model cannot account for the effects of skipping saccades on landing positions, since the configuration of inter-word spaces is the most important systematic difference between skipping saccades and one-step saccades at equal distances.

Although the models' inability to capture the effects of skipped words can be sufficiently deduced from its architecture alone we also run a numerical simulation to illustrate the model's performance on saccade-type contingent landing-position distributions. Result are presented in Figure 4.2 (gray symbols and lines), demonstrating that Engbert and Krügel's (2010) model generates the same predictions for one-step saccades and word-skipping saccades, i.e., all data points that correspond to the same launch-site distance fall on top of each other. In the next section, we will extend the model by Engbert and Krügel (2010) to overcome these limitations. We propose an explicit mathematical model of how readers use word boundaries (i.e., blank spaces between words) to compute the likelihood for the center of the next target word, which is then fed into the Bayesian procedure in Eq. (4.1).

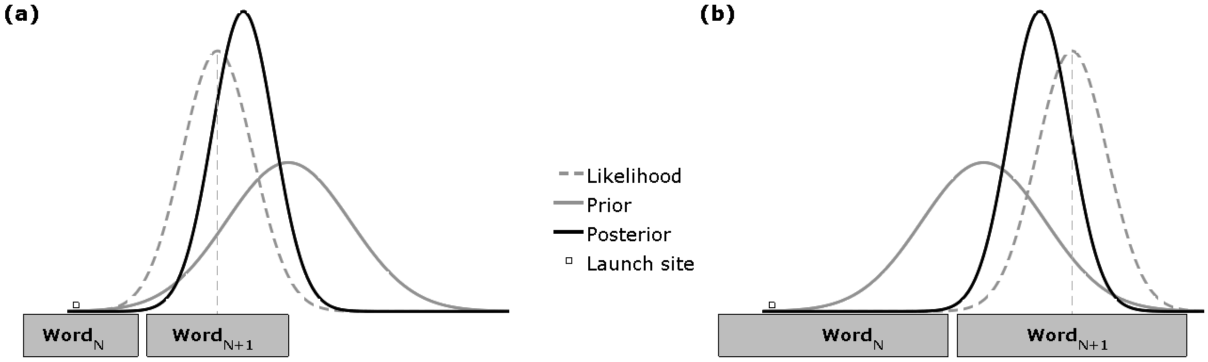

Figure 4.3. Schematic illustration of the Bayesian model of integrating noisy sensory information (i.e., the likelihood; dashed lines) and prior knowledge on target positions (solid grey lines). (a) The posterior probability distribution (solid black line) of near word-center positions is shifted into the second half of the word, which therefore generates a systematic overshoot of the word center on average. (b) If the word center is farther away from the launch site than predicted by the maximum of the prior distribution, the posterior estimate generates a systematic undershoot of the word center. Note that the precision of the posterior distribution ($1/\sigma^2_{\text{posterior}}$) is always larger than the precisions of the probability distributions that are used for Bayes' rule (i.e., likelihood and prior).

4.2 An improved model of saccade targeting in reading

Since word centers in normally printed texts do not represent readily identifiable positional cues (McConkie et al., 1988), we propose that the computation of the spatial parameters of target positions is based on sensory coding of blank spaces between words. Obviously, the position of the word center can be obtained as the spatial average of the positions of the word boundaries. In the following, we develop the mathematical details of our improved model of saccade targeting (see Figure 4.4 for an schematic illustration of the principles).

4.2.1 Delimitation of a spatially extended target region

When skipping the first word (word *N+1*) to the right of the currently fixated word *N* the saccadic landing position is strongly shifted towards the skipped word (Krügel & Engbert, 2010, see chapter 2). This happens regardless of whether the skipped letter string carries relevant semantic information or not (Krügel et al., 2012, see chapter 3), suggesting that only low-level visual properties are exploited by the visuo-motor system during saccade planning. To capture this general left-shift after skipping saccades compared to one-step saccades, we assume that the blank space between word *N* and word *N*+1 defines the beginning of the target region for the next progressive inter-word saccade, regardless of saccade type (i.e., for one-step as well as for skipping saccades). This blank space at the end of the launch-site word *N* is denoted as *S1* and its position relative to the launch site as x_{S1}. Furthermore, we assume that readers additionally use the blank space at the end of the target word, which is either word *N*+1 in one-step saccades or word *N*+2 in skipping saccades; in the following this secondary blank space is denoted as *S2* located at a distance of x_{S2} from the current fixation position.

4.2.2 Sensory localization of inter-word spaces

We assume that the two observations of *S1* and *S2* are unbiased and that the sensory noises in the two measurements are uncorrelated and Gaussian distributed with variances σ_{S1}^2 and σ_{S2}^2. Based on these assumptions we formulate the likelihoods of the observations of *S1* and *S2* as normally distributed conditional probability densities centered at the corresponding positions x_{S1} and x_{S2}, i.e., $q_1(x_{S1(\mathrm{o})}|x_{S1}) = \mathcal{N}(x_{S1(\mathrm{o})}, x_{S1}, \sigma_{S1}^2)$; $q_2(x_{S2(\mathrm{o})}|x_{S2}) = \mathcal{N}(x_{S2(\mathrm{o})}, x_{S2}, \sigma_{S2}^2)$. Furthermore, we postulate that the uncertainty associated with the observations of *S1* and *S2* is not constant, but depends on the following two principles: First, we assume that the uncertainty of the observations increases with increasing eccentricity of the signals, because of the progressive loss of visual acuity in the periphery of the visual field. For simplicity, we implement the standard deviations of the likelihood functions as a linear function of the distances x_{S1} and x_{S2}, i.e.,

$$\sigma_{Si} = c + \alpha x_{Si} \, , \tag{4.2}$$

where *i*=1, 2 specifies the blank space $S\{i\}$ considered. Equation (4.2) includes two free model parameters, a threshold *c* of the sensory uncertainty independent of the eccentricity of the signals and the magnitude α of the increase of the observational error with increasing eccentricity of *S1* and *S2*, respectively.

Second, we further assume that the uncertainty of the sensory measurement of the outer demarcation point of the target region (i.e., the position of *S2*) is additionally increased in intended word-skipping saccades, because here *S2* does not belong to the same word as *S1* (see Figure 4.4b). This assumption is supported by a large body of literature regarding the object-based deployment of visual attention showing that the allocation of visual attention is typically guided by object boundaries (Yantis & Serences, 2003; Moore, Yantis, & Vaughan, 1998; Egly, Driver, & Rafal, 1994). One robust experimental finding is that features, which are part of the same object, are processed less effortlessly and with more accuracy than features that belong to different objects (Duncan, 1984). Moreover, Baylis and Driver (1993) demonstrated that the evaluation of the relative spatial position of two visual cues is significantly hampered when the cues are part of the boundaries of different objects than when both cues belong to the boundaries of the same object. Therefore, we propose that the standard deviation of the likelihood function of the observation of *S2* in skipping saccades, σ_{S2}, increases as function of the length l_{skip} of the skipped word *N+1*. To compute the likelihood of the observation of *S2* in skipping saccades, we use a linear relation, i.e.,

$$\sigma_{S2} = c + \alpha x_{S2} + \lambda l_{\text{skip}}, \tag{4.3}$$

including the parameters c and α from Eq. (4.2) and the additional parameter λ, which reflects the magnitude of the effect of the skipped word length on σ_{S2}. Note that $l_{\text{skip}} = 0$ for one-step saccades.

4.2.3 Determination of the likelihood of a central target position by signal averaging

The spatial information derived from the signals *S1* and *S2* needs to be transformed into a point estimate for the saccade target. Engbert and Krügel (2010) compared different word-targeting strategies and were able to show that a model with the word center as the saccade target performed better than alternative models. Based on this theoretical support of the word center as the within-word target location, the most parsimonious strategy to identify a central target position based on the complementary sensory measures of the beginning and the end of the target region is to apply an averaging combination rule. Thus, we compute the sensory likelihood of a central target position x_{o}, given the signals *S1* and *S2* as the average of the corresponding likelihood functions, i.e.,

$$q(x_{\text{o}}|x_{S1}, x_{S2}) = \frac{1}{2}\left(q_1\left(x_{S1(o)}|x_{S1}\right) + q_2\left(x_{S2(o)}|x_{S2}\right)\right), \tag{4.4}$$

which forms another Gaussian probability density, $q(x_{\text{o}}|x_{S1}, x_{S2}) = \mathcal{N}(x_{\text{o}}, \mu_{\text{t}}, \sigma_{\text{t}}^2)$, with mean value

$$\mu_{\text{t}} = \frac{1}{2}(\mu_{S1} + \mu_{S2}) = \frac{1}{2}(x_{S1} + x_{S2}) \tag{4.5}$$

and variance

$$\sigma_{\mathrm{t}}^2 = \frac{1}{4}(\sigma_{S1}^2 + \sigma_{S2}^2). \tag{4.6}$$

4.2.4 Optimizing noisy sensory information according to Bayes' rule

Following Engbert and Krügel (2010), we finally assume that readers use Bayes' rule to reduce the uncertainty associated with the sensory estimate of the target position by combining the sensory likelihood with internal prior knowledge of the distribution of saccade targets during reading. We assume a Gaussian prior distribution of saccade-target positions, $p(x) = \mathcal{N}(x, \mu_x, \sigma_x^2)$ that can be estimated from reading data (see Engbert & Krügel, 2010). Using Bayes' rule (see Eq. (4.1)), we derive a normally distributed posterior distribution, $p(x|x_{\mathrm{s}1(o)}, x_{\mathrm{s}2(o)}) = \mathcal{N}(x, \mu_p, \sigma_p^2)$, which is proportional to the product of the unified sensory likelihood, $q(x_{\mathrm{o}}|x_{\mathrm{s}1}, x_{\mathrm{s}2})$, and the prior distribution $p(x)$,

$$p(x|x_{\mathrm{s}1(o)}, x_{\mathrm{s}2(o)}) \propto q(x_{\mathrm{o}}|x_{\mathrm{s}1}, x_{\mathrm{s}2})\, p(x). \tag{4.7}$$

As a result, the posterior probability of the target position has lower variance than each of the two cues (sensory and non-sensory) that inform the reader about the target position with, i.e.,

$$\sigma_p^2 = \frac{\sigma_{\mathrm{t}}^2 \sigma_x^2}{\sigma_{\mathrm{t}}^2 + \sigma_x^2}\ . \tag{4.8}$$

Furthermore, the maximum of the posterior (MAP = maximum-a-posteriori estimate) can be expressed as a weighted average of the means of the likelihood estimate and the prior estimate of the target position with weights that are assigned proportional to the relative reliability of the sensory (likelihood) and the non-sensory (prior) cues,

$$\mu_p = \frac{\sigma_x^2}{\sigma_{\mathrm{t}}^2 + \sigma_x^2}\mu_{\mathrm{t}} + \frac{\sigma_{\mathrm{t}}^2}{\sigma_{\mathrm{t}}^2 + \sigma_x^2}\mu_x. \tag{4.9}$$

This implies that the posterior is shifted towards the maximum of the prior, which leads to a systematic tendency to underestimate target distances that are more distant than on average and to overestimate unexpectedly short target distances. Given a stable prior distribution with

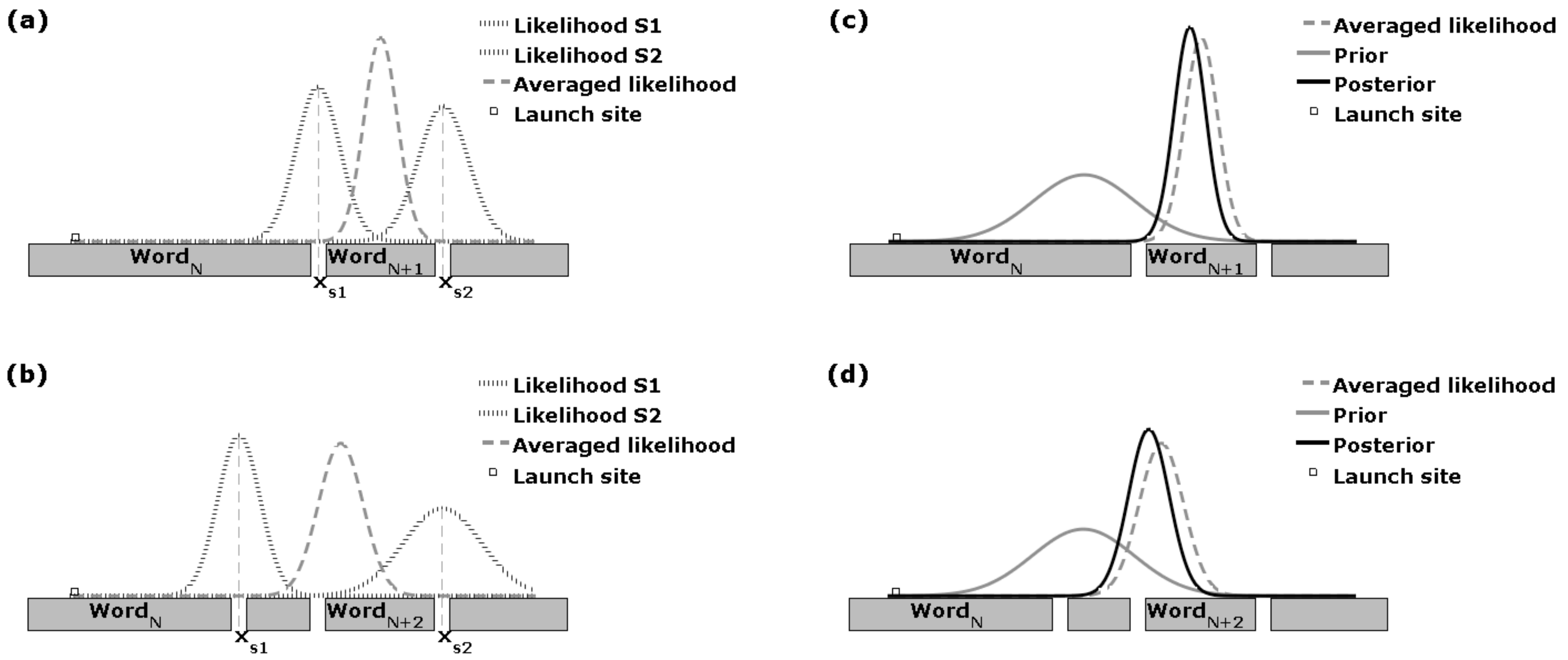

Figure 4.4. Schematic illustration of the improved Bayesian model of saccade planning that accounts for saccade type (one-step saccade vs. skipping saccade). Subplots (a) and (b) illustrate the likelihoods (dotted lines) for the blank spaces to the right of word *N* (i.e., *S1*) and the target word (i.e., *S2*), which is either word *N*+1 in one-step saccades, as illustrated in (a), or word *N*+2 in skipping saccades as illustrated in (b). Dashed lines represent the combined sensory estimate of the target-word center averaging the sensory estimates for *S1* and *S2*. In word-skipping saccades, the averaged likelihood is shifted towards an intermediate position located between the skipped word and the target word. Moreover, the averaged likelihood is less precise in skipping saccades than in one-step saccades because of the increased uncertainty within the individual sensory measurement of the position of *S2* in skipping saccades. Subplots (c) and (d) illustrate the influence of the prior distribution (solid grey lines). The posterior distribution (solid black lines), which is the result of multiplication of the sensory likelihood (dashed grey lines) with the prior distribution according to Bayes' rule, is shifted towards the maximum of the prior causing a systematic tendency to underestimate the distance of the launch-site for far target locations and to overestimate the launch-site distance for close target positions. The launch-site contingent shift is stronger in skipping saccades (compared to one-step saccades), since the computation of the posterior is based on less reliable sensory information in the skipping case.

a fixed reliability, the magnitude of the shift of the posterior towards the maximum of the prior increases with increasing uncertainty (i.e., reduced reliability) of the sensory likelihood.

4.3 Method

4.3.1 Reading experiment and data.

We analyzed eye-movement recordings from 275 skilled adult readers (age range: 16–84 years) with normal or corrected-to-normal vision each reading the Potsdam Sentence Corpus (Kliegl et al., 2006; Kliegl et al., 2004). The Potsdam Sentence Corpus consists of 144 German sentences comprising a total of 1138 words. Sentences were presented on the vertical centerline of a computer screen, one sentence at a time. Readers were seated in front of the computer display. A chin rest supported their heads. Eye-movements were recorded using EyeLink I and II systems (SR Research, Ottawa, Ontario, Canada). Saccades were detected with a binocular velocity-based algorithm (Engbert & Kliegl, 2003; Engbert & Mergenthaler, 2006).

4.3.2 Data preprocessing.

The first and last fixations in a trial, fixations on the first and last words of the sentences and fixations that were not classified with first-pass reading were excluded. A data set of 196,582 fixations was retained.

4.3.3 Cleaning data from mislocated fixations.

Within-word landing-position distributions in reading are broad and typically overlap with neighboring words (McConkie et al., 1988; Rayner, 1979; Vitu et al., 1990; Vitu et al., 2001). As a consequence, the distributions of initial fixations within words are biased by mislocated fixations (see discussion of this problem by McConkie et al., 1988). Mislocated fixations are the results of saccadic errors, i.e., the corresponding saccades were in fact intended to land on words next to the erroneously fixated words (Engbert et al., 2007; Nuthmann et al., 2005; McConkie et al., 1988). At the same time, fixations on unintended words also bias the estimates for probabilities that readers intend to skip a word or to refixate a word. We used an iterative, self-consistent estimation procedure (Krügel & Engbert, 2010, see chapter 2; Engbert & Nuthmann, 2008) to derive unbiased landing distributions, which are error-corrected for mislocated fixations. The method worked as follows (for mathematical details see Engbert & Nuthmann, 2008; Krügel & Engbert, 2010, see chapter 2): In a first step, truncated Gaussian functions were fitted to landing distributions for each word length, launch site, and saccade type and the obtained parameters of the Gaussian densities were summarized by saccade-type specific regression functions. Moreover, the probability to select words with a specific length as the saccade target was calculated from the data of the reading experiment. Second, an oculomotor model was simulated, which selects target words according to the obtained word-length based target-selection probabilities and generates distributions of landing positions using Gaussian landing parameters extracted from the regression functions obtained from the first step. Since the intended target word for each saccade in the simulation is known, simulated fixations within or outside the target word could be classified as well-located and mislocated fixations. On the basis of this classification, the proportion of mislocated fixations on each word was calculated from the simulation. In a last step, the distributions of mislocated fixations were subtracted from the corresponding experimentally observed distributions and the deviations of the simulated target-word selection probabilities from the reading experiment was used to adjust the probabilities for intended word skippings and refixations based on corresponding word lengths. This three-step procedure was repeated until the distributions and target-selection probabilities converged.

4.3.4 Model simulation.

We used a Nelder-Mead simplex, direct-search routine (The MathWorks, Natick/MA) to estimate the five free model parameters by minimization of the sum-of-squares error (SSE) between 90 individual landing-site distributions obtained from the reading experiment and the corresponding model predictions. For the simulation of the landing distributions in word-skipping saccades, the length of the skipped word was varied according to word-length based skipping rates obtained from the experiment.

4.4 Results

The predictions of our model are influenced by five free parameters. Among these parameters are the mean, μ_x, and the variance, σ_x^2, of the Gaussian prior distribution. Furthermore, according to Eqs. (4.2) and (4.3), three free parameters (i.e., c, α, and λ) were used to determine the standard deviations of the basic likelihood functions $q_1(.)$ and $q_2(.)$ associated with the sensory measurements of the cues *S1* and *S2* as a function of eccentricity and saccade type. We obtained the numerical values, μ_x=3.87, σ_x^2=3.44, c=1.65, α=0.09, and λ =0.70. Figure 4.5 shows a subsample of the Gaussian curves fitted to error-corrected landing-position distribution in one-step saccades and in skipping saccades for the Potsdam Sentence Corpus (black curves), each for a different combination of launch-site distance and target-word length, and the corresponding posterior distributions of the model (grey curves) based on our parameter estimates.

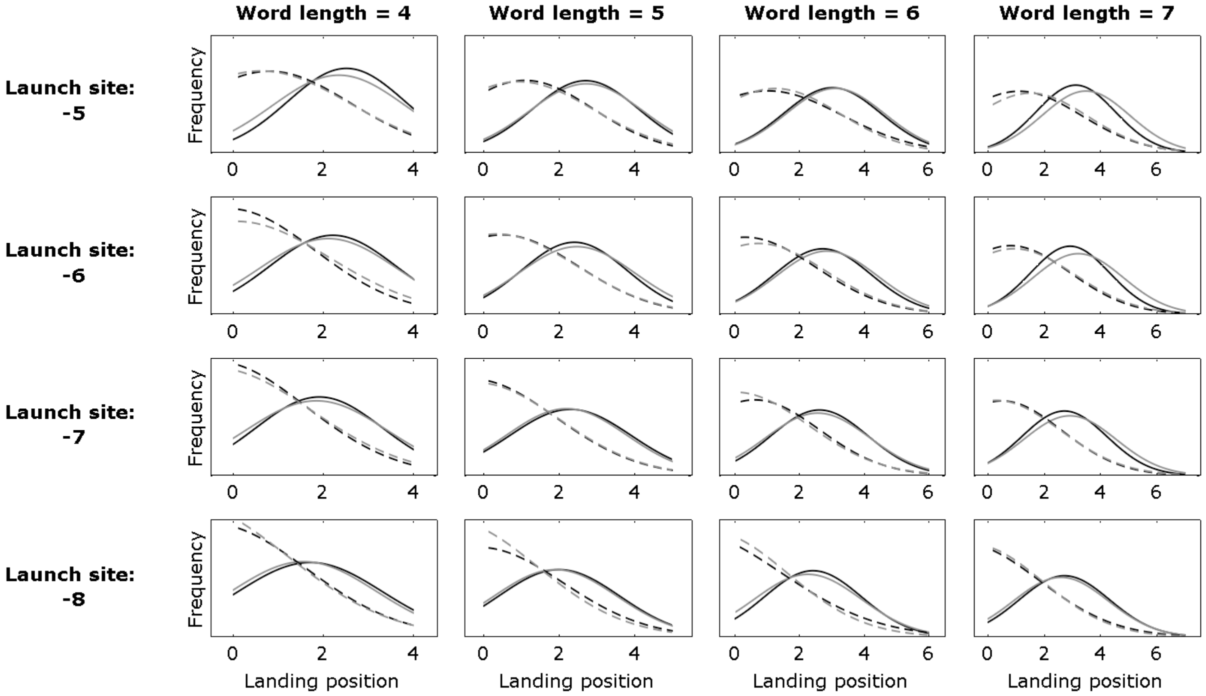

Figure 4.5. Within-word landing-position distributions in reading. Black lines correspond to truncated normal distribution fitted to experimentally observed data; grey lines represent model predictions. Plots within each line of panels show landing-position distributions for saccades, which were launched from equal distances towards the beginning of the target word, ranging from –8 letters to –5 letters. Each column of panels shows the landing distribution within words of a specific length (from 4-letter words to 7-letter words). Data and predictions are shown separately for one-step saccades (solid lines) and skipping saccades (dashed lines). A landing position of 0 corresponds to the beginning of the target word.

Figure 4.6 summarizes the goodness of fit of the model when compared to the experimental data. First, the model reproduced the characteristics of the landing-site distributions in one-step saccades. In particular, the comparison of the black circles (data) with grey circles (predictions) and the associated regression lines (Figure 4.4a) reveals that the model is able to accurately predict the average within-word landing positions in one-step saccades. Furthermore, though slightly overestimated, the predicted standard deviations of the landing distributions in one-word forward saccades are in a good agreement with the reading data and, most interestingly, the model captures the characteristic feature of a nearly constant variance of the landing position distribution in one-step saccades across a wide range of word-center distances.

The key results of our modeling approach is that the model was able to reproduce the complex pattern of main-effect differences and interaction-effect differences between the landing-position distributions in ones-step saccades and in skipping saccades for varying launch-site distances. The model generates a substantial left-shift of the average landing positions in skipping saccades compared to saccade landing sites in one-step saccades at equal launch-site distances. Moreover, as reflected by the steeper slope of the regression line for skipping saccades (Figure 4.6b), the model captures the enhanced size of the launch-site effect on mean landing positions in skipping saccades, i.e., a stronger systematic left-shift of the landing sites with increasing launch-site distances. At the same time the model accurately predicts much more pronounced landing-site random errors, when the eyes aim at next-but-one words (Figure 4.4b). Finally, the model also accounts for the almost constant variability of the within-word landing-position distributions in non-skipping saccades across a wide range of target distances and, simultaneously, for the considerable increase of the landing-site variability with increasing launch-site distances in word-skipping saccades.

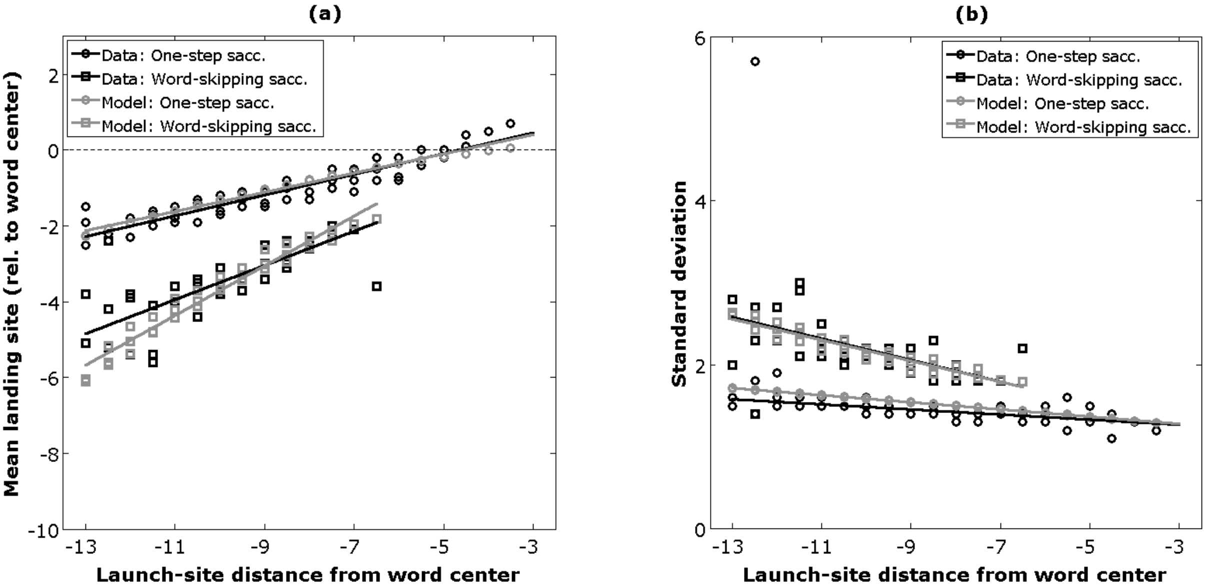

Figure 4.6. Evaluation of the new model of within-word landing distributions as a function of launch-site distance and saccade type (circles indicate values for one-step saccades, while squares represent corresponding values for word-skipping saccades). Black symbols represent estimates from the reading experiment; gray symbols show the corresponding simulated data of our new model. (a) Word-center based mean landing position as a function of saccadic launch-site distances to target-word centers. The zero value at the y-axis represents the word center (i.e., vanishing mean deviation). Positive values indicate overshoots of the word center and negative values undershoots. (b) Standard deviations of saccadic within-word landing-position distributions.

4.5 Discussion

Most theoretical models of eye-movement control during reading assume that saccades aim specifically at the center of a word that was selected as the next target (e.g., Engbert et al., 2005; for an overview see Reichle et al., 2003). Probably the strongest theoretical support for this assumption comes from a Bayesian oculomotor framework (Engbert & Krügel, 2010) demonstrating that a model, which programs a saccade to the center of the target word, gives a much better explanation of the experimental data than alternative strategies. At the same time, it is an unsolved problem how the center of a peripheral target word is identified by the visual system and how the obtained sensory information is integrated in the oculomotor system.

Here we proposed and analyzed a mathematical model of saccade planning, which makes explicit assumptions about the processes that translate the decision to move the eyes to a specific target word into a spatial target location based on the available visual information. Our model was developed in two steps. First, we implemented assumption on the sensory computation of the spatial position of the word center from independent sensations of blank spaces between words. Second, we integrated the computational framework for the identification of the word center with the Bayesian estimation proposed by Engbert and Krügel (2010).

The model qualitatively and quantitatively captured several important oculomotor effects at the same time. Our model accurately reproduced the systematic shift of within-word landing positions with varying distances of saccadic launch sites. Furthermore, the model gave a possible perceptual account for the effects of skipped words. We showed that the large systematic bias of saccadic initial landing positions in skipping saccades is compatible with the concept of words as perceptual objects, so that the preparation of skipping saccades is fundamentally more demanding for the attentional system than the preparation of one-step saccades. Moreover, we demonstrated by numerical simulations that less precise sensory information in skipping saccades is a potential factor to explain the increased landing-position variance that is associated with skipping saccades when compared to one-step saccades.

The Bayesian model by Engbert and Krügel (2010) offered a psychologically plausible explanation for the presence of the launch-site effect in reading that was derived from a very general framework of sensorimotor integration (Körding & Wolpert, 2004). In line with this framework, a noisy but unbiased observation of the position of the center of the target word was assumed, i.e., a Gaussian likelihood density centered at the position of the center of the target word. Furthermore, an internal representation of a probability density distribution of readers' a-priori expectation (i.e., the prior) was needed. As a result, the word center of the next target word is located at a characteristic distance from the fixation position. The combination of these two sources of information, current sensory information and memory representation of the past experience with the task, according to Bayes rule, gives a statistically optimal estimate of the true target position (i.e., the posterior). In general, the posterior is more precise than both the likelihood and the prior, and the sensory estimate of the target position (the likelihood) is shifted towards the prior.

There were two important limitations of Engbert and Krügel's (2010) model. First, the model was lacking a mechanism for the computation of the word center from visual input. Second, the model could not explain the qualitative differences of within-word landing positions between one-step saccades and skipping saccades.

The proposed modifications of Engbert and Krügel's (2010) model were constrained by the following three effects observed in experimental data: First, saccadic landing positions after skipped words are generally shifted towards the beginning of the words compared to the fixation positions in equally distant target words of one-step saccades. Thus, word skipping generates a general, launch-site independent left-shift of within-word landing positions. Second, within-word landing-site distributions of word-skipping saccades are characterized by an increased variance. Third, the systematic shift of average landing position with increasing launch-site distances is stronger in skipping saccades than in one-step saccades.

The most notable modification of Engbert and Krügel's (2010) model is that the center of the target word is no longer obtained as a direct sensory measurement. Rather we propose that the word center is computed from primary sensory input (word boundaries) by averaging across corresponding spatial positions (i.e., averaging of likelihood distributions). Over the last decades the word-center targeting hypothesis and the assumption that saccade planning is based on low-level text properties like launch-site distance, word lengths and interword-spaces coexisted in the reading literature, separated by the lack of a theory, which aims to explain how the word center is identified. Thus, the mechanism proposed here is a step towards bridging this gap. Another modification of Engbert's and Krügel (2010) model is that we now assume that the standard deviation of likelihood for the sensory information is linearly increasing with stimulus eccentricities and that it varies between the one-step saccades and skipping saccades.

These modifications are also preparing the way for generating the specific effects on landing positions when words are skipped during reading. We propose that the space after the fixated word *N* always constitutes the first of the two blank spaces, which are fed into subsequent computation of a single target point. Thus, effectively, we propose that in word-skipping saccades the words *N*+1 and *N*+2 are treated as a perceptual two-word target region for saccade planning. This is in line with previous theoretical explanations of the left-shift of landing distributions in word skipping (Radach, 1996; Radach & Kempe, 1993; Radach & McConkie, 1998; Krügel et al., 2012, see chapter 3; Drieghe, Pollatsek, et al., 2008). However, in contrast to Radach (1996) and Radach and McConkie (1998), we do not claim that the grouping of words in word skipping reflects an occasionally top-down controlled modification of the target location for the sake of further processing of the skipped word. Our analyses suggest that word grouping during saccade planning results from rather universal and highly automatic low-level perceptual processes.

Based on our explicit assumptions about perceptual processes and the computation of spatial saccade targets, our model makes highly specific and falsifiable predictions that will be tested in future research. For example, manipulating the sensory availability of word boundaries within a text should change the variance of the landing distributions, because it can be expected that such a manipulation would modulate the precision of the likelihoods and, in effect, would alter the posterior estimate of the target position. Furthermore, it may be particularly interesting to aim at an independent measure of the uncertainty within the sensory measurements of the spatial location of the word boundaries to validate our numerical estimates. Such an experiment could also be used to test our assumption that the likelihood of the sensory information of the spaces after words *N*+2 is less reliable than that of the spaces after words N+1, even if the spaces appear at equal eccentricities.

A related and particularly interesting question is how readers of unspaced languages like Chinese compute the spatial coordinates of saccade targets. Fundamentally, our model is based on word-boundary information. Yan and colleagues (Yan, Kliegl, Richter, Nuthmann, & Shu, 2010) argued that because word segmentation is more difficult without strong segmentation cues, Chinese readers aim at word centers when they were able to parse the parafoveal word units but aim at word beginnings if parsing failed. In agreement with this view, we think that the time course of the word segmentation process is critical for saccade planning in unspaced languages. More specifically, since our model does not include assumptions on the temporal dynamics of the saccade planning processes, its generalizability to unspaced writing systems must remain an open question for future work.

Finally, current models of eye-movement control during reading typically omit to make assumptions about the visual and oculomotor processes generating the spatial target position (see Reichle et al., 2003 for an overview). Rather these models typically sample fixation positions based on the purely statistical model by McConkie et al. (1988). However, it has been pointed out earlier by Krügel and Engbert (2010, see chapter 2) that the simplification of modeling fixation positions without considering word skipping will induce a number of inaccuracies and problems. On the one hand, taking saccade type into account will result in substantially different fixation position within the target words, which is important because where readers fixate within words is among the most important predictors of fixation duration (Vitu et al., 2001). On the other hand, the large additional left shift of the landing distributions in intended skipping saccades will also increase the number of fixations on unintended words to the left of the target word (i.e, mislocated fixations). The model presented here can in principle be implemented in all computational model of eye-movement control during reading (e.g., E-Z Reader, Reichle et al., 2003; SWIFT, Engbert et al., 2005), which generally assume that saccades are generated towards previously selected target words and that the signal of moving the eyes towards the target word must be somehow transformed into a pinpoint spatial coordinate.

5. Final conclusion

In this final chapter we briefly summarize the key results of the previous chapters and assemble what we have learned about the computation of the word center during reading. In addition, we consider several implications of our work for further empirical studies based on eye-movement recordings to investigate both normal reading and more fundamental visuo-motor principles as well as for current computational models of eye-movement control during reading.

5.1 What we have learned

From a general perspective, the main insight from the work presented in chapter 2 is that saccades' initial landing positions within words in reading are not only determined by the distance of the target word from the launch site, which was the widely shared point of view for more than 20 years of reading research after the seminal work of McConkie et al. (1988). With word skipping we identified a further important factor with surprisingly systematic and strikingly strong effects on saccades' landing positions, the most important of which are shifts of two or more letters further to the left after skipped words as compared to the landing sites of one-step saccades aiming at equally distant target words. Furthermore, we found substantially larger variances in the landing distributions after skipped words and stronger changes of both the mean and variances of the landing distributions in skipping saccades with changing launch sites. Using large corpus data from normal sentence reading we demonstrated that the change of landing positions after skipped words is not limited to the skipping of particularly short words as suggested by Radach and McConkie (1998), but turned out to be consistent across a wide range of target word distances and word lengths. Thus, these findings significantly advance the existing knowledge about where the eyes go in reading when proceeding further in a line of text.

Our findings raised the question whether the word-skipping contingent change of landing positions represents a strategically intended departure from the word center as the functional saccade target during reading or whether it reveals more fundamental constraints of the perceptual processes associated with the computation of the word center when a word is skipped. To answer this question we continued our investigations with a highly controlled single saccade experiment (see chapter 3), in which participants in half of the trials skipped a string of x-letters when moving their eyes towards a target word. We qualitatively replicated the changes of landing position after skipping saccades, although an additional left-shift of landing positions after skipping was detrimental to the actual task of reading the words after the x-letter string. This led us to reject the hypothesis that readers intentionally employ different functional saccade targets in word skipping relative to one-step saccades during reading. To the contrary, we drew the conclusion that the effect of skipped words in reading most likely resulted from rather low-level perceptual processes associated with the computation of the spatial position of the saccade target. Moreover, our findings suggest that the spaces between words play an important role in the perceptual computation of the saccade target and that particularly the space between the current word *N* and the skipped word *N+1* interferes with the computation of the center of the target word *N+2* in skipping saccades.

Chapter 4 focused on the development of a computational model of the sensory processes associated with the computation of the spatial position of the word center as functional saccade target during reading. The model is based on two key principles. Firstly, we assumed that there is no direct route to the perception of the word center for saccade planning. According to our model, the word center is derived as a perceptual estimate based on the sensory localization of word boundaries provided by the spaces between words. Secondly, we assumed that readers use principles of Bayesian inference to compute an optimized estimate of the most likely position of the word center as a combination of the primary sensory estimate and non-sensory information such as prior knowledge about the probability distribution of saccade target positions in reading. Within these two key principles, we propose explicit assumptions regarding further sensory constraints and perceptual processes, which influence the generation of a specific pinpoint target-position estimate based on the selection of a (spatially extended) target word. Using numerical simulations we demonstrated that our model simultaneously captures most of the reported effects of launch-site distance and word skipping on saccade landing positions with a fairly high quantitative agreement.

5.2 Implications for models of eye-movement control during reading

The discovery of the effect of skipped words on saccade landing positions likely sets a new benchmark for current computational reading models such as E-Z Reader (Reichle et al., 2003), SWIFT (Engbert et al., 2005), Glenmore (Reilly & Radach, 2006), and SERIF (McDonald, Carpenter, & Shillcock, 2005), which all aim at providing a comprehensive framework to account for both the temporal and the spatial aspects of eye movement control during reading. While most of these models make specific and significantly different assumptions about the processes that lead to the selection of target words for saccades to aim at during reading, they typically sample saccades' landing positions according to the statistical linear landing-position model provided by McConkie and colleagues (McConkie et al., 1988). As this is purely based on the distance of the target word, one immediate consequence of our results is the revealing of remarkable inaccuracies in the approximation of initial within-word fixation positions within these computational reading models. For example, our results suggest that McConkie et al.'s statistical model (McConkie et al., 1988) largely underestimates the agreement of initial within word fixation positions and the word center in one-step saccades, but largely overestimates the level of agreement in word-skipping saccades. However, a realistic approximation of landing positions is important for computational models, because initial fixation positions within words influence both fixation durations on the target word as well as the probability that a further fixation at a different position within the same word is necessary to complete the processing of the word. Thus, inaccuracies in the determination of landing positions likely entail adverse repercussions for the modeling of fixation durations and selection of target words. One simple and effective way to eliminate these biases is to sample landing positions contingent on saccade type according to the regression models provided in chapter 2.

On the other hand, failing to make specific assumption about the perceptual processes for saccade planning after the selection of a target word represents a theoretical gap about a vital part of the control of eye-movements during reading. From our point of view, the present work demonstrates that the information about the position of the word center does not simply "appear" instantaneously with the selection of a target word for the next saccade. Instead, the perceptual computation of the word center is a fairly complex endeavor, which only begins with the selection of a target word, and which leads to strong systematic biases such as a difference of two or more letters in the landing sites of one-step saccades and word-skipping saccades. Thus, we consider it worthwhile to close this gap within current computational models of eye-movement control in reading. The computational model presented in chapter 4 can in principle be implemented in any computational reading model which agrees with the word-center targeting assumption.

5.3 Implications for experimental studies of reading based on eye movements

Mislocated fixations, i.e., fixations on unintended words, cause a number of difficulties for empirical studies of reading based on eye-movement recordings. Our discovery of substantial differences in the landing distributions after one-step saccades and word-skipping saccades also provides an opportunity to improve the current knowledge about the occurrence of mislocated fixations during reading. Mislocated fixations are a consequence of the mutual overlaps of landing distributions of neighboring words. Thus, it is obvious that the strong modulation of the means and variances of landing distributions with saccade type has important consequences for the likelihood that saccades miss target words and erroneously generate mislocated fixations on unintended words. Interestingly, while it has been widely acknowledged that mislocated fixations are ubiquitous in reading and that they most likely appear near the word boundaries, surprisingly little attention has been paid to the fact that the proportions of mislocated fixations on the words and letters in a reading experiment are largely constrained by the observed landing distributions. In other words, the experimental observation of saccades' within-word landing distributions in a reading experiment makes it possible to derive fairly accurate estimates about the expected proportions of saccades that missed the target word and, in turn, to estimate the expected proportion of mislocated fixations among the observed fixations on the neighboring words in a reading experiment.

Based on the work of Engbert and Nuthmann (2008; see also Engbert et al., 2007; Nuthmann et al., 2005) we developed a computational algorithm to numerically approximate the proportions of mislocated fixations within the landing distributions of our corpus of reading data that must be expected according to the modulation of saccades' systematic and random errors as a function of both the distance of the target word and word skipping. In our eyes, this self-consistent estimation technique based on the experimental observations of landing positions and target-selection probabilities is the most promising approach to counter the problems that arise from mislocated fixations for studies of reading by means of eye-movement recordings.

As an example, mislocated fixations play an important role for the interpretation of so-called parafoveal-on-foveal effects in reading, which take center stage in the highly controversial debate about a strictly serial or principally parallel timing of the lexical processing of words during reading (Drieghe, Rayner, & Pollatsek, 2008; Kliegl, 2007; Kennedy, 2008; Reichle, Liversedge, Pollatsek, & Rayner, 2009; Risse & Kliegl, 2012).

Parafoveal-on-foveal effects refer to influences of properties of the parafoveal words *N+1* or even *N+2* to the right of a currently foveated word *N* on the duration of the fixation of word *N* (Kennedy, 1998; Drieghe, 2011; Hyönä, 2011). While these effects could indicate that multiple words are processed simultaneously, this interpretation is highly disputed based on the notion that these effects could in principle also solely origin from mislocated fixations on word *N*. According to the mislocated fixation argument, it is assumed that readers sometimes erroneously fixate at word *N* (because the incoming saccade missed the intended target word *N+1*) but in fact process the originally intended word *N+1*. Unfortunately, there is no way to positively identify mislocated fixations in a reading experiment. As a consequence, it is difficult to decide between these two conflicting hypotheses.

However, it is largely undisputed that mislocated fixations in reading can contribute to the generation of parafoveal-on-foveal effects. The decisive point is whether or not parafoveal-on-foveal effects in reading are exclusively generated by mislocated fixations, which translates into the question whether or not experimentally established parafoveal-on-foveal effects are fully compatible with the proportions of mislocated fixations that must be expected at the fixation positions at which these effects occur. As already mentioned, the proposed algorithm in chapter 2 can be employed to gain estimates of the most likely proportion of mislocated fixations among all observed fixations at each letter position within a reading experiment. Interestingly, in a recent work Kliegl, Krügel, and Engbert (2013) submitted these estimates derived from our algorithm as a predictor to a statistical linear-mixed effects model based on fixation durations. Notably, they reported that the significant effects of the frequencies and predictabilities of the parafoveal words *N+1* on the fixation times of words *N* maintained or even increased when the corpus-analytic results were statistically controlled for the expected proportions of mislocated fixations according to the experimentally observed landing distributions. They concluded that these parafoveal-on-foveal effects could not be due solely to mislocated fixations. This example demonstrates that the estimation algorithm for mislocated fixations in reading experiments presented in chapter 2 has important implications for experimental studies of reading based on eye-movement recordings.

Our work in chapter 3 makes a further important contribution to the subject of mislocated fixations during reading. In this chapter we tested whether the word-skipping effect in reading is the signature of a top-down controlled change of the intended saccade target from the center of a selected target word into a central position within a two-word target region consisting of the words *N+1* and *N+2* (see Radach, 1996; Radach & McConkie, 1998). This alternative would also strongly undermine the plausibility of the concept of mislocated fixations for a large number of saccades in reading, because the classification of fixations to be mislocated strictly depends on the assumption that readers principally aim at individual words during reading. However, based on the results of our experiment, we rejected this top-down interpretation of the word-skipping effect (see also Drieghe, Pollatsek, et al., 2008). Hence, our central conclusion from the single-saccade experiment in chapter 3, i.e., that saccadic landing positions after skipped words are unintentionally relocated due to highly automatic low-level perceptual processes, also lends support to the theoretical plausibility of the concept of mislocated fixations for cases of word skipping during reading.

5.4 Implications for basic oculomotor research

Two different conceptual frameworks, which both have their origin in basic oculomotor studies, have been very influential as an explanation of what determines initial landing positions within words during reading: the range-error concept (Kapoula, 1985; McConkie et al., 1988) and the center-of-gravity assumption (Findlay, 1982; Coren & Hoenig, 1972; Vitu, 1991a; Vitu, 2008). The range-error model, which is the dominant theoretical position in the field, postulates that a reader’s experience with the range of target distances establishes a systematic bias in the oculomotor system to generate saccades of an average length. The center-of-gravity assumption, on the other hand, postulates that the eyes are pulled towards a weighted spatial average (i.e., the so-called center of gravity) of all the letters within an effective peripheral window to the right of the fixation position. Notably, the range-error view focuses on a readers experience with global properties of eye-movement behavior during reading and largely ignores attributes of the stimulus (except the distance of the word center from the launch site). In sharp contrast, the center-of-gravity theory entirely focuses on attributes of the stimulus (i.e., the visual configuration of the reading material) and ignores the reader’s experience.

The Bayesian model of saccade planning based on averaged spatial positions of inter-word spaces combines aspects of both approaches. It considers perceptual processes on the level of specific stimulus attributes involving multiple elements of the visual configuration as well as explicit process-related assumptions as to how prior knowledge gained through experience influences the computation of the saccade target during reading. The model demonstrates that experience-based and stimulus-based approaches do not represent mutually exclusive frameworks, but likely focus on different aspects of a multi-faceted process. Furthermore, the formulation of assumptions about how these different levels interact during the planning of eye movements opens a research perspective, which goes beyond a consideration of saccade planning during reading. For example, we have demonstrated in chapter 4 that the stronger launch-site effect in word-skipping saccades may be a specific consequence of the interactions from experienced-based and stimulus-based processes. According to the model, the larger effect in skipping saccades has its starting point in the sensory processes on the stimulus level, which are associated with larger inaccuracy of the sensory measurement of the target position due to the involvement of an additional word in word skipping. However, any change in the reliability of one of the two information systems, sensory and non-sensory, also changes the relative contributions of both systems on the calculation of the target position. In this case, the reduction of reliability in the sensory estimate increases the weight of the prior knowledge. The result of this interaction is an increased shift of the likelihood towards the prior, i.e. a larger launch-site effect in skipping saccades.

This mechanism may be of some general importance since it suggests a solution to the long-standing puzzle why the systematic launch-site contingent mean-shift of landing positions is surprisingly large in reading, while the size of the effect in simpler oculomotor tasks is at most marginal (Kapoula, 1985; Kapoula & Robinson, 1985) or even completely absent (Coëffé & O'Regan, 1987; Findlay, 1982; Vitu, 1991b). From our perspective, these differences appear highly plausible. No or little experience with an arbitrary experimental task in combination with a less complex and easily identifiable stimulus (i.e., weak prior knowledge and highly reliable sensory input) may be the reason for a small, possibly even absent, launch-site effect in a typical basic oculomotor paradigm. In contrast, skilled reading is characterized by years of experience and a perceptually more demanding stimulus configuration, which most likely generates just the opposite effect. Thus, in our eyes, the interaction of experience and expectations on the one side and perceptual processes on the level of the concrete stimulus on the other side truly deserves further research efforts.

5.5 Concluding remarks

The present work "Eye-movement control during reading: Factors and principles of computing the word center for saccade planning" aimed at investigating how readers identify word centers for the programming of saccadic motor commands during reading. Our results have enlarged the current knowledge showing that beyond the launch site, word skipping is a further important variable for the generation of progressive inter-word saccadic eye movements during reading (*factors*) and that saccade planning in reading is based on the sensory measurement of spaces between words which are integrated by an average-combination rule and optimized with prior knowledge according to Bayes' rule (*principles*). We expect that our work provides critical boundary conditions for computational reading models and generates new hypotheses and predictions which will stimulate further research. The present series of three studies based on three different methodological approaches is also a demonstration of how well the "three disciplines of scientific psychology" (Kliegl, 2007), i.e., corpus analyses, experiments, and computational modeling, complement each other. Finally, although we aimed primarily at contributing to the understanding of the normal reading process, we also believe that our work, particularly our process-oriented perceptual model for saccade planning, represents a valuable perspective on the scientific study of reading difficulties such as dyslexia (Krügel, Klein, Esser, & Engbert, 2013).

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