The “Where” and “When” of Eye Fixations in Reading

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Abstract

To investigate eye-movement control in reading, the present thesis examined three phenomena related to the eyes' landing position within words, (1) the optimal viewing position (OVP), (2) the preferred viewing location (PVL), and (3) the Fixation-Duration Inverted-Optimal Viewing Position (IOVP) Effect. The influence of several variables on parameters of the OVP, PVL and/or IOVP function was systematically explored: word length, launch site distance, word frequency, as well as five experimental manipulations. First, word center was identified as the OVP, that is the position within a word where refixation probability is minimal. With increasing launch site distance, however, the OVP was found to move towards the word beginning. Several possible causes of refixations were discussed. The issue of refixation saccade programming was extensively investigated, suggesting that pre-planned and directly controlled refixation saccades coexist. Second, PVL curves, that is landing position distributions, show that the eyes are systematically deviated from the OVP, due to visuomotor constraints. By far the largest influence on mean and standard deviation of the Gaussian PVL curve was exhibited by launch site distance. Third, it was investigated how fixation durations vary as a function of landing position. The IOVP effect was replicated: Fixations located at word center are longer than those falling near the edges of a word. The effect of word frequency and/or launch site distance on the IOVP function mainly consisted in a vertical displacement of the curve. The Fixation-Duration IOVP effect is intriguing because word center (the OVP) would appear to be the best place to fixate and process a word. A critical part of the current work was devoted to investigate the origin of the effect. It was suggested that the IOVP effect arises as a consequence of mislocated fixations, i.e. fixations on unintended words, which are caused by saccadic errors. An algorithm for estimating the proportion of mislocated fixations from empirical data was developed, based on extrapolations of landing position distributions beyond word boundaries. As a new central theoretical claim it was suggested that a new saccade program is started immediately if the intended target word is missed. On average, this will lead to decreased durations for mislocated fixations. Because mislocated fixations were shown to be most prevalent at the beginning and end of words, the proposed mechanism generated the inverted U-shape for fixation durations when computed as a function of landing position. The proposed mechanism for generating the effect is generally compatible with both oculomotor and cognitive models of eye-movement control in reading.

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List of Abbreviations

ABBREVIATION	MEANING
α	level of statistical significance
ANOVA	analysis of variance
df	degrees of freedom
Eta (η^2)	effect size
Exp.	Experiment
Fig.	Figure
FIRSTFD	first fixation duration
freq	word frequency
F_x	F value in analysis of variance
IOVP	inverted optimal viewing position
LS	launch site
M	mean
MS	mean square
MSE	mean square error
n.a.	not available
OVP	optimal viewing position
p	probability
P_2	probability of 2 fixations
P_{3+}	probability of 3 or more fixations
P_{REGR}	regression probability
P_{SKIP}	skipping probability
PSC	Potsdam Sentence Corpus
PVL	preferred viewing location
SD	standard deviation
SE	standard error
Sec.	Section
SECFD	second fixation duration
SFD	single fixation duration
SPSS	Statistical Package for the Social Sciences
SRE	saccadic range error
$\text{TIME}_{\text{TOTAL}}$	total reading time
t_x	*t*-quantile (*t*-test)
vs.	versus
wl	word length

1 Introduction

Reading is a complex skill involving a range of different “low level” visuomotor and “higher level” cognitive processes (e.g., visual information processing, word recognition, attention, oculomotor control). There is now a great body of research showing that eye movement data reflect these moment-to-moment processes in reading (for a review, see Rayner, 1998).

The aim of this introductory chapter is to provide a very brief survey over the field of eye movements and information processing in normal reading. First, saccades and fixations are introduced as basic oculomotor events in reading (Sec. 1.1). Second, and from a more general point of view, eye-movement behavior in reading is considered as a sequence of individual decisions about *when* and *where* to move the eyes (Sec. 1.2). Third, theoretical perspectives on eye-movement control in reading are roughly sketched and contrasted as cognitive control theories vs. oculomotor theories (Sec. 1.3). Finally, theoretical background, structure, and design of the present thesis are outlined.

1.1 Types of Saccades

For illustrational purposes, Fig. 1.1 shows the eye movement trajectory of a participant reading a sentence of the Potsdam Sentence Corpus (PSC). Contrary to our subjective impression, during reading the eyes do not move smoothly across the sentence. Instead, the eyes make short and rapid movements, called *saccades*. Between saccades, the eyes remain relatively still during *fixations*. During saccades, vision is suppressed, that means little or no visual information processing takes place (Matin, 1974). Thus, visual information about the text is only extracted during fixations. Therefore, reading is similar to a slide show in which short segments of text are displayed for approximately a quarter of a second (Reichle, Rayner, & Pollatsek, 2003). For illustration, Fig. 1.1c displays the temporal change of both x- and y-positions of the right eye with fixations as numbered clusters and saccades as rapid eye movements.

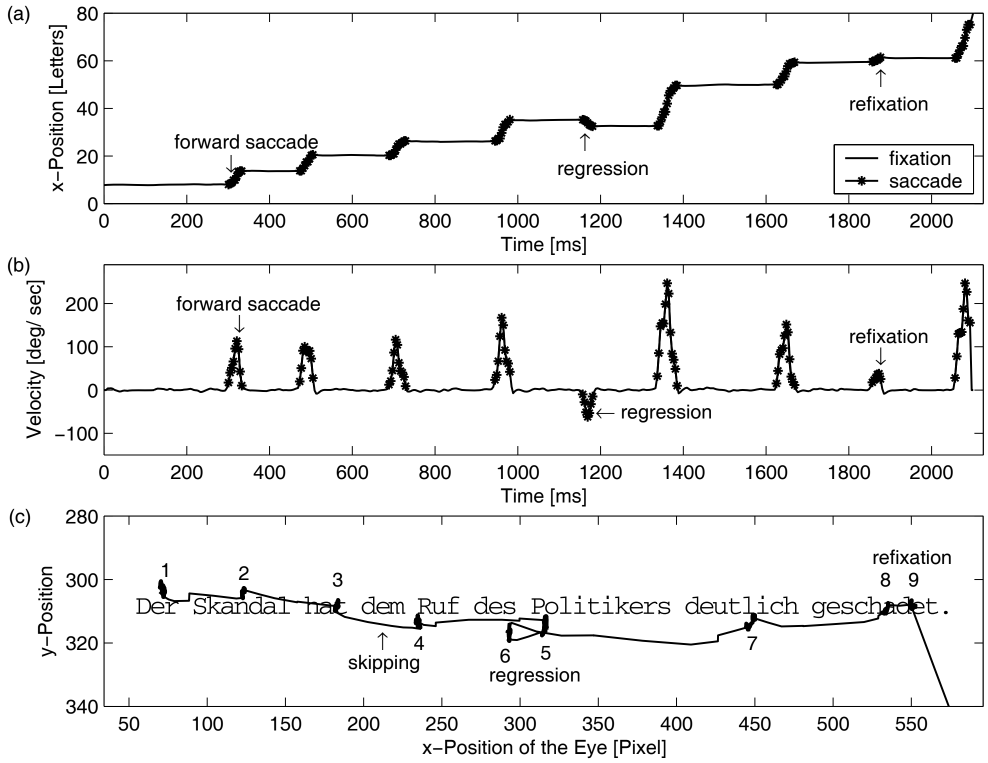

Fig. 1.1 (a) Space-time diagram of eye movements from the right eye while reading a sentence from the Potsdam Sentence Corpus. (b) Time series of *x*-positions of the right eye transformed to velocities. (c) Plot of the *x*-position of the right eye against the *y*-position.

In reading, most saccades are made in the direction of the reading system (i.e., from left to right in the German language). The majority of saccades departing from a specific word (*n*) go to the immediately following word (*n*+1). For example, in the sentence displayed in Fig. 1.1, the reader starts with successively fixating the words „Der“, „Skandal“, and „hat“. Quite frequently, saccades departing from word (*n*) skip the next word (*n*+1) and instead go to the word beyond that word (*n*+2). Words that are skipped are usually short (e.g., Brysbaert & Vitu, 1998), and oftentimes highly predictable from the preceding context (e.g., Balota, Pollatsek, & Rayner, 1985), and/or words with a high frequency of occurrence in the respective language (e.g., Radach & Kempe, 1993). In the example sentence, the word „dem“ is skipped. Apparently, the word was fully processed in the parafovea while the eyes were fixating on the preceding word “hat”. The word “des” was also skipped initially. However, after fixation 5 on „Politiker“, the reader is regressing back to the word „des“ (Fixation 6). Roughly 10-15% of all fixations are inter-word regressions, bringing the eyes to positions left of the current word boundary (Rayner, 1998). Regressions predominantly land on words *n*-1 or *n*-2 (Radach & McConkie, 1998; Vitu & McConkie, 2000). Furthermore, long and/or difficult words are refixated, i.e., they receive additional fixations before the reader leaves the word (here „geschadet“ at the end of the sentence), while forward refixations are more frequent than backward refixations; together they make up about 15% of all fixations.

For the present work, the following terminology and/or classification is relevant: Intra-word saccades, another term for refixation saccades, move the eyes within word boundaries while inter-word saccades move the eyes to a different word. According to the direction of the eye movement, saccades can be further contrasted as progressive (forward, right-directed) vs. regressive (backward, left-directed) movements.

A given fixation location defines the *landing position* within a word, and also the takeoff point or *launch site* for the next target word. Launch site distance is defined as the distance, in letters, between the launch site of the last saccade and the beginning of the target word.

1.2 When and Where to Move the Eyes

Eye movements during reading are generally considered to be the result of two classes of decisions, one spatial (*where* to move the eyes) and one temporal (*when* to move the eyes). Although there is not complete consensus on this issue (e.g., Vitu, 2003), the “where” decision appears to be word-based: Each saccade intends to move the eyes to a specific word (McConkie & Zola, 1984). Therefore, the “where” decision can be analyzed in a hierarchical way: First, which word is selected as the target of the next saccade, and second, where do the eyes actually land given the selection of a target word for a particular saccade (McConkie, Kerr, & Dyre, 1994)? As far as the first question is concerned, it is still under debate to what degree words are selected as the result of cognitive processing or low-level oculomotor strategies (Starr & Rayner, 2001; see also Sec. 1.3). As for the second question, which is of special relevance for this thesis, the idea has been put forth that reading saccades have a functional target location which is the center of the word (McConkie, Kerr, Reddix, & Zola, 1988) because word center is considered to be the optimal viewing position (cf., McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; see also Chapter 3, pp. 62). However, due to error in the perceptual or oculomotor system, the eyes do not always land precisely at their intended target location within a word or not even at the intended target word (McConkie *et al.*, 1988). Thus, the performance aspect of the “where” decision (Radach & McConkie, 1998), comprises within-word over- and undershoots causing the considerable variance associated with landing position distributions (see Chapter 4, pp. 100) as well as the phenomenon of mislocated fixations (see Fig. 6.2, p. 145).

The temporal aspect of eye-movement behavior, the “when” decision, is captured by fixation duration measures. Over the past 30 years a great deal of research has been conducted to determine the relationship between fixation durations and linguistic and/ or oculomotor variables. First, fixation durations are influenced by low-level nonlinguistic factors. They systematically vary with word length, within-word fixation position, and launch site distance (Vitu, McConkie, Kerr, & O’Regan, 2001). Second, it has been shown that also various lexical, syntactic, and discourse factors influence fixation durations on words (for a review, see Rayner, 1998). In particular, there is evidence that fixation duration is affected on-line by the following variables: word frequency, lexical ambiguity, semantic relationship, contextual constraint, syntactic complexity, anaphora, and coreference (Rayner *et al.*, 1996). Thus, fixation durations in reading are sensitive to local processing difficulty.

The distinction between “when” and “where” decision finds support at the neurophysiological level of saccade programming. Neurophysiological research suggested that there are at least two descending pathways in the neurophysiology of the oculomotor system. One carries spatial information (“where”), while the other serves as a trigger and is involved in temporal aspects of saccades (“when”).[1] As for eye-movement data in reading, there is some evidence indicating that decisions about where to fixate next and when to move the eyes are made somewhat independently (see Reichle *et al.*, 2003, for details). However, sometimes the two decisions may overlap (see Rayner, Kambe, & Duffy, 2000). In general, any serious account of eye-movement control in reading must explain *where* the reader fixates next and *when* the reader moves his/her eyes (Rayner & Fischer, 1996).

A main focus of this thesis is to investigate how within-word fixation location affects fixation duration, i.e. the problem of coupling of “where” and “when” pathways.

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[1] The concept of separate “where” and “when” pathways was first introduced by oculomotor physiologists (Van Gisbergen, Gielen, Cox, Bruijns, & Kleine Schaars, 1981).

1.3 Theories on eye-movement control in reading: oculomotor theories vs. cognitive control theories

Theoretical models of eye-movement control during reading can be classified into two general categories (cf., Rayner, Sereno, & Raney, 1996; Starr & Rayner, 2001): (1) *Cognitive models* are based on the assumption that ongoing cognitive processing drives eye movements during reading, while (2) *oculomotor models* hypothesize that eye movements are mainly controlled by low-level oculomotor or visuomotor processes and are only indirectly related to ongoing cognitive processing. Cognitive models can be further divided into models driven by *sequential attention shifts* (SAS) and models of *guidance by attentional gradients* (GAG) (for details of this classification see also Engbert, Longtin, & Kliegl, 2002; Reichle *et al.*, 2003).

As far as the "when" and "where" decision is concerned, cognitive models focus primarily on the temporal aspect of eye behavior, but the spatial aspect of this behavior is also taken into account. Oculomotor models, on the other hand, focus primarily on the spatial aspect of eye behavior.

Cognitive Models, SAS: E-Z Reader

For SAS models the serial allocation of visual attention from one word to the next is the "engine" driving eye movements. This architecture was first proposed by Morrison (1984). The currently most advanced SAS model is E-Z Reader (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999; Reichle *et al.*, 2003; Pollatsek, Reichle, & Rayner, 2006). An SAS model with fewer internal states based on advanced stochastic methods was proposed as an alternative (Engbert & Kliegl, 2001, 2003c).

In E-Z Reader, word processing is strictly serial while saccades can be programmed in parallel. The development of this model was motivated by two important findings incompatible with Morrison's (1984) model. First, preview benefit, the shortening of processing time on subsequent words originating from time spent on the foveal word, is modulated by foveal processing load (Henderson & Ferreira, 1990; Kennison & Clifton, 1995). Second, one often observes "spillover" effects due to word frequency (Rayner & Duffy, 1986; see also Kliegl, Nuthmann, & Engbert, 2006); that is, lower frequency words induce longer fixation durations not only locally but also lengthen the fixation duration on the succeeding word. Recent further developments of E-Z Reader include landing position distributions (Reichle *et al.*, 1999) and improved refixation behavior (Reichle *et al.*, 2003; Pollatsek *et al.*, 2006), thus extending the model to reproduce effects generated by oculomotor control principles, in addition to effects of lexical processing. The interface between cognition and eye-movement control in E-Z Reader was reevaluated recently (Pollatsek *et al.*, 2006).

Cognitive Models, GAG: SWIFT

In contrast, GAG models assume that attention is distributed continuously as a gradient. As a consequence, more than one word can be attended to (and processed) in parallel. The SWIFT[2] model (Engbert, Nuthmann, Richter, & Kliegl, 2005; Engbert *et al.*, 2002; Kliegl & Engbert, 2003; Engbert, Kliegl, & Longtin, 2004; Richter, Engbert, & Kliegl, 2006; Laubrock, Kliegl, & Engbert, in press) is such a GAG variant that assumes spatially distributed lexical processing. As a key feature of the SWIFT model, a general mechanism underlying all types of saccades is implemented. Also, the fundamental separation between “where” and “when” pathways was adopted in the SWIFT model as a key principle of model design. Thus, the temporal and spatial control of saccades was implemented with as little interaction as possible (Principle II). For details on the seven core principles implemented in SWIFT as well as the numerous empirical phenomena that are reproduced by the model, it is referred to Engbert *et al.* (2005).

In both the SWIFT model as well as the E-Z Reader model, eye movements are driven by word recognition. Thus, the well-established link between cognitive processes of word recognition and eye-movement control (see above) has been implemented (see Reichle *et al.*, 2003, for a recent review; Engbert *et al.*, 2005). In all cognitive models, a specific word is selected as a saccade target. Thus, if oculomotor errors lead to a mislocated fixation, it should affect processing.

Oculomotor Theories

The most prominent example of an oculomotor model is O’Regan’s strategy-tactics model (1990, 1992; O’Regan & Lévy-Schoen, 1987). According to this theory, the eyes’ initial landing position in a word largely determines how long to fixate on a word and where to go next. It is proposed that readers adopt a global “strategy” (e.g., careful or risky reading) that coarsely influences fixations and saccades. It is also

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[2] (Autonomous) **S**accade-Generation **W**ith **I**nhibition by **F**oveal **T**argets.

proposed that readers implement local, within-word "tactics" that are based on lower level, nonlexical information.

Work by McConkie *et al.* (1988), and McConkie *et al.* (1989) can also be seen in this oculomotor tradition. A more recent primary oculomotor model was suggested by Yang & McConkie (2001, 2004). The key assumption of their competition-interaction theory is that the timing of saccades is largely independent of lexical processing. However, processing difficulty can inhibit the oculomotor system from initiating a saccade program. This notion has clear affinities with SWIFT's notion of autonomous saccade generation with (time-delayed) foveal inhibition (Engbert *et al.*, 2005).

Proponents of both types of models (cognitive vs. oculomotor) can point to various empirical results in support of the model they advocate (see Rayner & Fischer, 1996). However, the two classes of theories on eye-movement control in reading basically define the extremes of a continuum. Any successful model will likely have to accommodate both "cognitive/attentional" and "visual/oculomotor" aspects (Radach & Kennedy, 2004). The SWIFT model (Engbert *et al.*, 2005) can be considered as a successful theory combining elements of both traditions.

When discussing empirical findings from a theoretical point of view, it will be predominantly referred to the SWIFT model, the E-Z Reader model, and the strategy-tactics model. The respective model assumptions that are relevant for the respective issue under discussion will be explained in context. Furthermore, the work by McConkie *et al.* (1988), and McConkie *et al.* (1989) will be extensively discussed.

1.4 Thesis Outline

Following this introductory chapter, the thesis is organized into nine major chapters. Starting with Chapter 2, six reading experiments are introduced. The rationale behind the experimental manipulations is explained, and global analyses are presented. The following three chapters introduce three landing-position dependent phenomena. First, the *optimal viewing position* (OVP) is introduced (Chapter 3). The OVP can be operationally defined as the position at which refixation probability is minimal (cf., McConkie *et al.*, 1989, for continuous reading; O'Regan & Lévy-Schoen, 1987, for isolated words). It will be shown that locations near the word center appear to be optimal both for saccade targeting and foveal word processing, supporting and extending previous research. Second, due to visuomotor constraints, the eyes are systematically deviated from this OVP, creating the difference between the optimal and the *preferred viewing location* (PVL), the latter being the focus of Chapter 4. Third, it is investigated how fixation durations vary as a function of landing position (Chapter 5). Supporting results from a recent research report (Vitu *et al.*, 2001), it will be shown that fixations located at word center tend to be longer than those falling near the edges of a word. Chapters 3 to 5 are each organized in a similar way. First, the basic phenomenon is introduced, based on analyses of the original reading experiment (Exp. 1, $N = 245$). Second, corpus analyses are complemented by investigating how experimental manipulations influence parameters of the OVP function (Sec. 3.2), the PVL curve (Sec. 4.4), and/or the IOVP function (Sec. 5.2).

The Fixation-Duration IOVP effect is intriguing because word center as the OVP would appear to be the best place to fixate and process a word, as there is a greater chance of all letters being recognized. Therefore, the theoretical focus of this thesis is the introduction of a new explanation for the puzzling IOVP effect (Chapter 6). Fixation-Duration IOVP effects will be explained as a consequence of mislocated fixations caused by saccadic errors.

The refixation OVP effect (Chapter 3) is related to theoretical questions regarding the occurrence of refixations: (1) what circumstances give rise to refixations, and (2) when are they programmed. The “when” question tackles the question of pre-programming vs. directly controlled programming of refixation saccades. Both issues will be investigated.

Measures of eye movements in reading are influenced by both “low level” visuomotor variables like word length and launch site distance, as well as “higher level” cognitive variables like word frequency. The large data set from the original reading experiment (Exp. 1, $N = 245$) allowed orthogonal data sampling by word length and launch site distance (Chapter 7), and/or word length and word frequency (Chapter 8). Therefore, the thesis is rounded off by examining the influence of launch site distance and/ or word frequency on OVP, PVL and IOVP.

In Chapter 9, results are summarized and discussed. Finally, some concluding comments will be provided in Chapter 10.

1.5 Design

Data presented to introduce a particular phenomenon (OVP, PVL, IOVP) will be based on analyses of the original reading experiment (Exp. 1, $N = 245$). These analyses will be complemented by investigating how experimental manipulations (Exp. 2 through 6) modulate specific aspects of these phenomena. As will be shown in the following chapter, a certain number of readers (30-47) participated in each of these reading experiments. Readers participating in Experiments 3, 5, and 6 were university students. Therefore, their eye movement behavior was contrasted with all university students ($n = 107$) having read the original version of the Potsdam Sentence Corpus (Exp. 1). Thus, a between-subject design was created post hoc. Note that the same control group was used for all three experiments. In Experiment 4, however, the great majority of the 31 participants were high-school students. Consequently, the control group consisted of age-matched high-school students who read the original version of the Potsdam Sentence Corpus. Finally, in Experiment 2 participants read a *z*-transformed version of the Potsdam Sentence Corpus. For these participants, “normal” reading data were available, allowing a within-subject design.

2 General Introduction of Experiments and Global Analyses

All reading experiments reported were based on the Potsdam Sentence Corpus. Starting point is the so-called original reading experiment (Exp. 1) which is introduced in Sec. 2.1. In particular, the Potsdam Sentence Corpus is described in detail (Sec. 2.1.3), followed by considerations regarding procedure (Sec. 2.1.4) and analyses (Sec. 2.1.5).[3] In addition, five experimental manipulations are introduced (Exp. 2 through 6). In each experiment, a certain aspect of the original reading experiment (Exp. 1) was manipulated. In the following, the motivation behind these experimental manipulations is outlined briefly.

Given the ongoing controversy between the two theoretical camps in the field (cf., Sec. 1.3, p. 13), one of the currently most relevant research issues is to determine the relative influences of low-level perceptual factors and higher-level cognitive factors on eye movements during reading (Starr & Rayner, 2001). One possibility is to consider a set of predictors known to influence, for example, fixation durations (e.g., Kliegl *et al.*, 2006). Another approach is to create a reading-like condition which shares none of the higher level lexical, semantic, or syntactic processes involved in normal reading. This was done in Exp. 2 where a *z*-string version of the Potsdam Sentence Corpus was created as an oculomotor control condition to the original reading experiment (Sec. 2.2, pp. 25).

In all reading experiments employed in the Potsdam laboratories, a chin rest is used to somewhat reduce participants head movements. In a further control condition to the original reading experiment, a much more constrained viewing condition was created in that participants' heads were fixed with a bite bar instead of being stabilized with a chin rest only (Exp. 4, Sec. 2.4, pp. 38). Exp. 3 was designed to investigate whether landing-position related phenomena, especially PVL and OVP, could be positively influenced by making the OVP of selected words more salient to the readers (Sec. 2.3, pp. 33). The saliency manipulation was realized by marking the OVP of selected words in red. A further experiment investigated whether and to what extent the temporal and spatial aspects of eye-movement behavior in reading are influenced when the letter contrast is considerably reduced (Exp. 5, Sec. 2.5, pp. 41). In a last experiment, changes in landing position were artificially induced by recurrently displacing the sentence during saccades (Exp. 6, Sec. 2.6, pp. 45). Since vision is

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[3] Note that these explanations apply to all experiments reported in this thesis.

suppressed during saccades (Matin, 1974), the sentence displacements were not consciously perceived by the readers. A more global question to investigate was whether the sentence shifts induced specific oculomotor responses. In addition, the experiment was created to test the so-called pre-programming hypothesis of refixation saccades.

The Potsdam Sentence Corpus was constructed by Ellen Grabner. The original reading experiment (Exp. 1, Exp. 4) as well as the reading with low contrast experiment (Exp. 5) were programmed in C; the programming was done by Sabine Kern. Experiments 2, 3, and 6 were programmed by the author of this thesis. The software was written with MATLAB (The Mathworks, Inc.), using the Psychophysics Toolbox extensions (Brainard, 1997) as well as the Eyelink Toolbox extensions (Cornelissen, Peters, & Palmer, 2002).

2.1 Original Reading Experiment (Experiment 1) – Method

2.1.1 Participants

Altogether 245 participants contributed to the original reading experiment. The data base consists of four sub-samples: 110 university students, *M* = 22.22, *SD* = 3.53, range 18 to 38 years), 70 older adults (*M* = 69.61, *SD* = 4.73, range 60 to 84 years), 41 high-school students (*M* = 17.80, *SD* = 0.93, range 16 to 20 years), and 24 subjects of middle age (*M* = 43.70, *SD* = 8.29, range 21 to 57 years).

Participants were further tested with a multiple-choice measure of vocabulary (Lehrl, 1977) and the digit symbol substitution test from the HAWIE intelligence test for adults (Wechsler, 1964). Detailed information on the age, sex, and eye dominance of participants as well as their performance in the measure of vocabulary and the digit symbol substitution test can be found in Appendix A.

All participants were native speakers of German. Sessions lasted about one hour. Participants were paid an equivalent of 5 € / hour or received credit in partial fulfillment of study requirements.

2.1.2 Apparatus

Sentences were presented on the center line of a 21-inch EYE-Q 650 Monitor (832 x 624 resolution; frame rate 75 Hz; font: regular New Courier 12) controlled by an Apple Power Macintosh G3 computer. Participants were seated 60 cm in front of the monitor with the head positioned on a chin rest. Thus, letters subtended 0.38° of visual angle.[4] Data were collected in two laboratories with identical equipment and setup. Eye movements from eighty-five participants were recorded with two SR EyeLink I Systems (SMI) operating with a sampling rate of 250 Hz. A further 160 participants were tested with two SR Research EyeLink II Systems with a sampling rate of 500 Hz. Calibrated eye position was recorded accurately at the level of letters.

2.1.3 The Potsdam Sentence Corpus

Word length. The Potsdam Sentence Corpus comprises 144 German sentences (1138 words). They were constructed with the goal to represent a large variety of grammatical structures around a set of target words (one or two per sentence; see below) that are uncorrelated in length and frequency. Sentence lengths range from 5 to 11 words with a mean of 7.9 words. Excluding the first word of each sentence which was not used in the analyses, frequencies of word lengths 2 to 13+ are: 54, 222, 134, 147, 129, 92, 72, 66, 20, 25, 16, and 17. (The category 13+ contains seven words of length 14 to 20.)

Printed frequency. CELEX Frequency Norms (Baayen, Piepenbrock, & Rijn, 1993) are available for all 1138 words. Excluding the first word of each sentence, the corpus contains at least 74 words in each of five logarithmic frequency classes [class 1 (1 - 10 per million): 249 words; class 2 (11 - 100): 206 words; class 3 (101 - 1000): 243; class 4 (1001 - 10000): 227; class 5 (10001 - max): 74 words]. The CELEX corpus is based on approximately 5.4 million words.

Predictability. Predictability of words was collected in an independent norming study with an incremental cloze task (for details see Kliegl, Grabner, Rolfs, & Engbert, 2004). Excluding the first word of each sentence, the corpus contains at least 73 words in each of five logit-based predictability classes [class 1 (0 to -1.5): 506 words; class 2 (-1.5 to -1.0): 111 words; class 3 (-1.0 to -0.5): 114 words; class 4 (-0.5 to 0): 88 words; class 5 (0 to 2.553): 175 words].

Target words. Each sentence contained one target word selected from the CELEX database contributing to a 2 × 2 × 3 design with word class (noun vs. verb), printed frequency (high: > 50 occurrences/million vs. low: 1 to 4 occurrences/million), and word length (short: 3, 4 letters, medium: 5 to 7 letters, long: 8, 9 letters); there were 12 sentences in each cell of this design. The position of the target word ranged from being

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[4] For a number of participants tested in the Golm-Lab, the monitor-subject distance was 50 cm so that one letter subtended 0.45° of visual angle.

the second to the second word from the last word in the sentence; mean word position is 4.9. For a subset of 32 sentences, two directly adjacent target words (a verb-noun or noun-verb sequence) set up a four-factorial mini-design with the frequency of the second target word as a fourth orthogonal factor in addition to word class, frequency, and length of first word; the additional target word of a sentence was of the same length as the first one. There were two sentences contributing to each cell of the 2 × 2 × 2 × 2 design. In Appendix E, target words are set in italics; for the subset of the first 32 sentences, additional target words are underlined.

2.1.4 Procedure

Participants were calibrated with a standard nine-point grid for both eyes. They were instructed to read the sentence for comprehension and fixate a dot in the lower right corner of the monitor to signal the completion of a trial. After validation of calibration accuracy, a fixation point appeared on the left side of the center line on the monitor. If the eye tracker identified a fixation on the fixation spot, a sentence was presented so that the midpoint between the beginning and the center of the first word was positioned at the location of the fixation spot. Therefore, each sentence-initial word was read from a word-specific optimal viewing position (e.g., O'Regan & Lévy-Schoen, 1987; Rayner, 1979). Sentences were shown until participants looked to the lower right corner of the screen. Then, the sentence was replaced (a) by an easy three-alternative multiple choice question pertaining to the current sentence on 27% of the trials which the participant answered with a mouse click, (b) a fixation spot indicating the beginning of the next trial which participants then initiated by fixating the fixation point or (c) a complete recalibration with the nine-point grid after 15 sentences each. In addition, the experimenter carried out an extra calibration if the tracker did not detect the eye at the initial fixation point within two seconds.

2.1.5 Analyses

Eye movement data from reading the 144 sentences were screened for blinks and loss of measurement. All 245 participants were considered when analyses were based on data that were averaged across all participants. For participant-based statistics, however, 19 participants were excluded because they generated less than 100 valid sentences (3 university students, 9 older adults, 5 high-school students, 2 middle-aged adults).

2.1.5.1 Saccade detection

For saccade detection a velocity-based detection algorithm originally developed for the analyses of microsaccades (Engbert & Kliegl, 2003b) was used. For an example sentence, Fig. 1.1a (p. 10) shows the *x*-position of the right eye as a function of time. In Fig. 1.1b, *x*-positions were transformed into velocities. Changes of velocity values are used to distinguish saccades from fixations (Engbert & Kliegl, 2003a).

First, the time series of eye positions is transformed to velocities with a weighted moving average of velocities over five data samples to suppress noise. As a consequence of the random orientations of the velocity vectors during fixations, the resulting mean value is effectively zero (Fig. 2.1). In this representation, saccades can be identified by their velocities which are clearly separated from the kernel of the distribution, that is saccades are “outliers” in velocity space. For example, the outlier to the left represents the regressive saccade (see Fig. 1.1, p. 10). Second, for a given trial (i.e., sentence) median-based velocity thresholds were computed. Because these computations are performed separately for horizontal and vertical velocity components, the corresponding thresholds define an ellipse in the velocity space (Fig. 2.1). However, when reading an one-line sentence the eyes predominantly move horizontally so that the horizontal component is most important. If there are more than three (for data from SR EyeLink I system) and/or 4 (for data from SR EyeLink II system) velocity samples falling outside this ellipse, these sequences are defined as saccades. Third, reading saccades are seen as binocular events with binocularity defined by a temporal overlap criterion for the data from the right and left eye (for details see Engbert & Kliegl, 2003a).

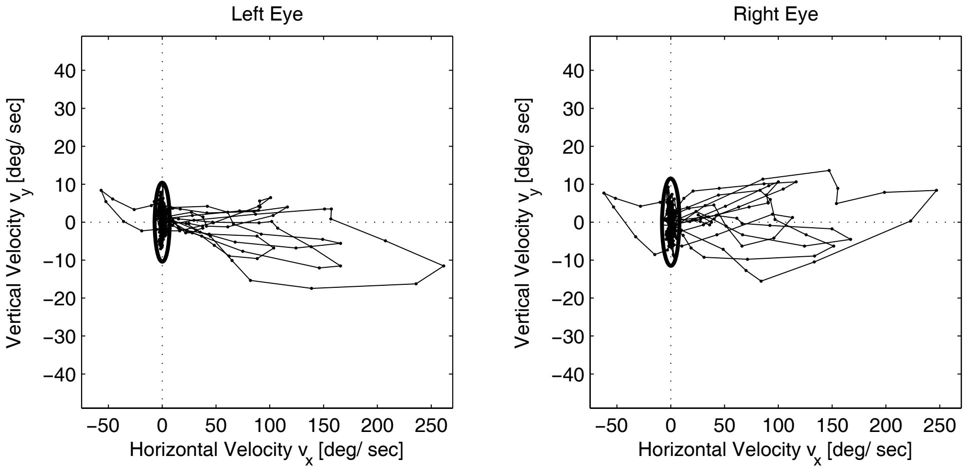

Fig. 2.1 Example of binocular saccades, (a) data recorded from the left eye, (b) data recorded from the right eye. The trajectory from Fig. 1.1c is now plotted in 2D velocity space. The ellipse in each panel is defined by the velocity thresholds of the saccade detection algorithm. If there are more than three (for data from SR EyeLink I system) and/or 4 (for data from SR EyeLink II system) velocity samples falling outside this ellipse, these sequences are defined as saccades.

Note that the algorithm is able to detect very small saccades (microsaccades). Therefore, reading saccades were defined as saccades with amplitudes of at least one letter. This categorical definition was adopted because in eye-movement research investigating reading, fixation positions on words are usually described in terms of which letter of the word a fixation is on.

Saccades were detected as binocular eye movements; still, all analyses were based on the data from the right eye. Following saccade detection, data were further processed to create a matrix format where each row represents one fixation, and numerous columns carry important information about this fixation and/or the preceding saccade.

2.1.5.2 Statistical analyses

The methodology used in eye movement studies of continuous reading typically involves the construction of experimental sentences or short passages of text that include critical target words (e.g., Rayner & Fischer, 1996). Relevant independent variables (e.g., word frequency) are systematically manipulated and their effects on eye movement measures are observed.

An alternative to this experimental-control approach is the quasiexperimental approach where corpora of natural text are being read. For example, Radach (1996) had four German-speaking graduate students reading a German translation of the first two parts of the book *Gulliver's Travel* (about 160 book pages). A common analysis strategy for natural reading data is *post-hoc* selection of words from the reading material for an orthogonal design (e.g., Kliegl, Olson, & Davidson, 1983; Radach & McConkie, 1998; Radach & Heller, 2000). Within a subset of data, a number of variables is controlled (held constant) while a target variable is systematically investigated by comparing cases with different values of that variable. The disadvantage of this orthogonal sampling strategy, however, is that effects may sometimes be influenced by variables not considered in the sampling scheme or mediated by hidden interactions (Radach & Kennedy, 2004). On the other hand, in cases where aspects of eye behavior cannot be experimentally manipulated, such as where the eyes go during free viewing, this method allows to separate out the effects of different variables on eye behavior (Radach & McConkie, 1998).

The Potsdam Sentence Corpus combines aspects from both approaches. Participants were not engaged in a completely natural reading situation where they would, for example, read parts of a book. Rather, the 144 one-line sentences were constructed with the goal to represent a large variety of grammatical structures around a set of target words (one or two per sentence) that are uncorrelated in length and frequency. Thus, analyses of target words allow to assess the independent contributions of these important variables to visual and lexical processes. However, we can also examine how results based on this experimental-control approach generalize to all words of the Potsdam Sentence Corpus. For example, Kliegl *et al.* (2004) used multiple regression (Lorch & Myers, 1990) as a statistical-control technique to determine the effects of correlated predictors.

Data from the original reading experiment[5] (Exp. 1, N = 245) are used to introduce certain phenomena (OVP, PVL, IOVP). These analyses will be complemented by investigating how experimental manipulations (Exp. 2 to 6) modulate specific aspects of these phenomena. Here, data from the original reading experiment serve as control groups (see Sec. 1.5, p. 17).

In general, almost all analyses are based on *all* words of the Potsdam Sentence Corpus, instead of target words only. For the theoretical questions pursued here, *landing position* is certainly the most relevant variable. Therefore, for analyses on OVP, PVL, and IOVP, data were broken down by word length and landing position within a word.

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[5] Note that a portion of these data base was used for research reports on the effects of word length, frequency, and predictability on inspection durations and inspection probabilities (Kliegl *et al.*, 2004), as well as fixation durations before word skipping (Kliegl & Engbert, 2005).

For some analyses based on data from the original reading experiment (Exp. 1), the huge data base allowed orthogonal data sampling by word length and launch site distance (Chapter 7), and/or word length and word frequency (Chapter 8).

All analyses were performed with MATLAB, and statistics were calculated in SPSS. If not stated otherwise, an alpha level of .05 was adopted for all statistical tests.

To get a first impression of the effect of experimental manipulations, word-based summary statistics comprising four measures of fixation duration as well as four fixation probability measures were computed (Chapter 2). Each measure was broken down by five logarithmic word-frequency classes and/or 11 word length categories, respectively. Thus, these analyses did not take the correlation between both variables into account. The word-based summary statistics were complemented by computations of frequency distributions for fixation durations and saccade lengths.

2.2 Experiment 2 – Mindless Reading (*Z* String "Reading") as an Oculomotor Control Condition

Experiment 2 served as an oculomotor control condition to the original reading experiment (Exp. 1). The experiment is strongly related to a paradigm introduced by Vitu, O'Regan, Inhoff, & Topolski (1995). In their study on "mindless reading", all letters in a text were replaced with *z*s (henceforth, *z* strings) while punctuation and spacing were preserved. Participants were instructed to scan the text as if they were reading. The results indicated that the global characteristics of saccades were quite similar for the "mindless reading" of *z* string text and normal reading (but see Fischer, 1999; Rayner & Fischer, 1996, for differences in saccade control between these tasks). Thus, the *z* string "reading" condition provides information about oculomotor behavior in the absence of lexical processing demands that can be compared against the eye behavior of the same readers in a normal reading task.

2.2.1 Participants, Apparatus, Materials and Procedure

Thirty-one university students (21 women and 9 men, 1 n.a.; mean age = 22.6 years, SD = 2.6 years) who responded to an advertisement at Potsdam University were recruited and consented to participate in the experiment. They received either course credit or a 5 € payment. All participants had normal or corrected-no-normal vision. Detailed information on the age, sex, and eye dominance of participants as well as their performance in a measure of vocabulary and the digit symbol substitution test can be found in Appendix B.

Consistent with Vitu *et al.* (1995), the only instruction given to the participants was that they should pretend that they were reading each line of *z* strings. A potential problem with this manipulation is that it cannot be known exactly what task the subjects set for themselves when asked to perform the *z* string "reading" task. Therefore, to prevent participants from adopting a certain strategy, the *z* sentences of the Potsdam Sentence Corpus were randomly mixed with 36 normal filler sentences (Appendix C).

Twenty-six of the 31 participants also participated in the original reading experiment (Exp. 1), the remaining five subjects had participated in Exp. 3. Thus, for a given participant, both *z* string "reading" data as well as "normal" reading data were available, creating a within-subject design.[6] Participants were tested with an SR Research EyeLink II (500 Hz) system in the Golm-Lab.

2.2.2 Global Analyses

2.2.2.1 Four fixation duration and four probability measures

For a given experiment, the impact of the experimental manipulation will be first evaluated by considering word-based summary statistics comprising four measures of fixation durations as well as four fixation probabilities, each measure being broken down by five logarithmic word-frequency classes and/or 11 word length categories, respectively.[7]

Fixation durations. Inspection times are central for evaluating visual information processing in reading. The fixation duration data will be represented by non-overlapping measures. Single fixation duration was calculated for all cases in which a word received exactly one fixation. For the evaluation of refixations, first fixation duration[8] as well as second fixation duration are used. These measures are limited to first-pass reading, i.e. fixations after regressions to previous words do not contribute –

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[6] Actually, altogether 46 university students had read the *z*-string version of the Potsdam Sentence Corpus (see Appendix B). However, 15 subjects were excluded from analyses. For one subject, no comparison data from the original version of the reading experiment were available. One subject had participated in another reading experiment which is not part of this thesis. Furthermore, 13 subjects had participated in the reading with sentence shifts experiment (Exp. 6). However, this manipulation strongly affected landing position distributions.

[7] The analysis scheme was adopted from Engbert *et al.* (2005).

[8] In the following, first fixation durations are computed as an average of all cases with a second (or more) fixations, i.e. excluding single-fixation cases. Traditionally, however, first fixation durations include single-fixation cases (e.g., Rayner, 1998).

irrespective of whether this word had been skipped or fixated initially. Finally, total reading time was calculated, the sum of all fixations regardless of the eye's trajectory which generates these fixations.[9]

Fixation probabilities. The four measures of fixation durations are complemented by four measures of fixation probabilities. The probability measures characterize the spatial aspect of eye-movement patterns. Based on first-pass reading, four measures were calculated: (1) skipping probability, (2) the probability for two fixations, (3) the probability for three or more fixations[10], as well as (4) regression probability or, more precisely, the probability that a word is the target of an inter-word regression.

Effects of word length versus word frequency.

For each participant, means of the above eight measures of fixation durations and fixation probabilities, broken down by 11 word length categories (Fig. 2.2c and d) and/or five logarithmic word-frequency classes (Fig. 2.2a and b), were computed and then averaged across participants (exact values for means and standard deviations in Appendix I, Tables I1, and I2).

While word length is considered to be an important low-level visuomotor variable, word frequency is seen as a higher-level cognitive variable capturing lexical processing. In a mindless reading condition it appears to be inappropriate to consider frequency plots (Fig. 2.2a and b). However, word length and word frequency are highly correlated (-.64 for 994 corpus words, i.e., excluding the first word of each sentence). Therefore, it is interesting to see whether frequency effects emerge, solely due to this high correlation. Of course, the CELEX frequency values of the original words were used for analyses.

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[9] This category is necessary to collect all possible fixation sequences in a "rest" category.

[10] By definition, the probability for a single fixation can be calculated by one minus the sum of the probability for skipping and the probabilities for two and three or more fixations.

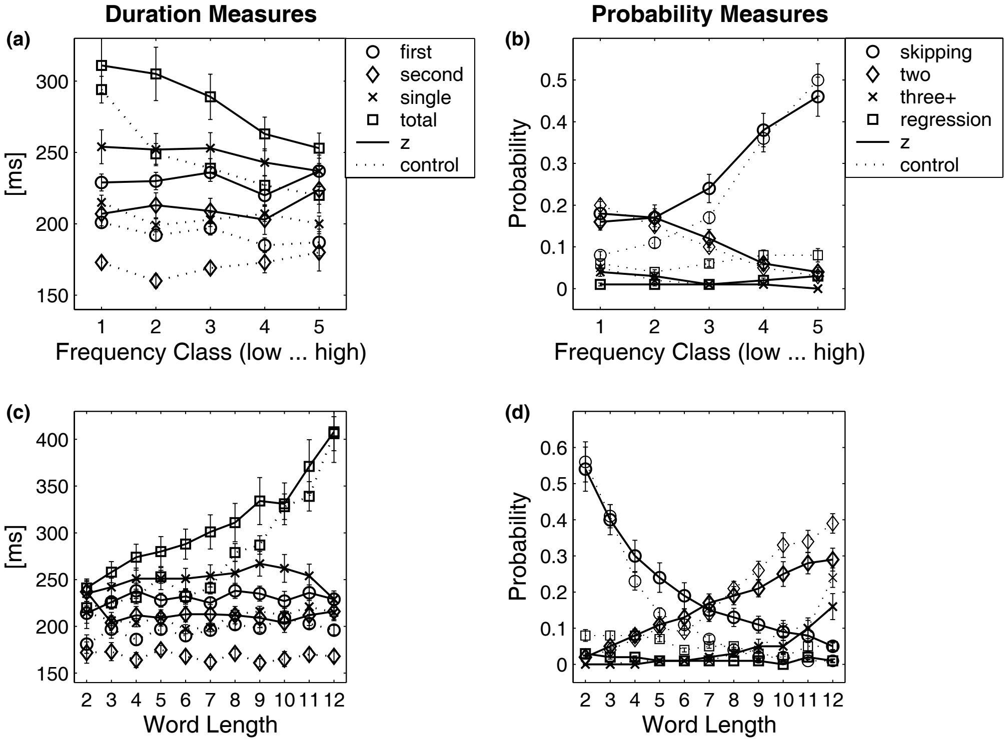

Fig. 2.2 Word-based summary statistics of different eye-movement measures by word frequency classes and by word length classes for *z* string "reading" data (*z*) vs. normal reading control data. (a) Mean durations for first, second and single fixation durations and total reading time as a function of word frequency class. Results for *z* string "reading" data are given by the solid line, while results obtained for normal reading control data are dotted. (b) Probabilities for skipping, two fixations, three or more fixations and the probability that a given word is the target of a regression as a function of word frequency class. (c) Mean durations for the same measures as in (a) as a function of word length class. (d) Probabilities as a function of word length class.

For each of the eight measures, a repeated measures analysis of variance (ANOVA) with "experimental condition" (mindless vs. normal reading) and "word length" (11 categories) and/or "word frequency" (5 logarithmic classes) as within-subject factors was employed. A complete report about the inferential statistics is provided in Appendix I, Table I3. In the following, significant effects are highlighted.

First, in the *z* string "reading" condition, participants produced significantly longer durations for single, first, and second fixation durations [$F(1,30) > 11.04$, $p < .05$] but not for total reading time [$F(1,30) = 2.67$, $p = .113$]. These results are in line with previous reports (Vitu *et al.*, 1995; Rayner & Fischer, 1996). For single fixation duration as well as total reading time, there was also a significant effect of word length. Furthermore, the word length effect interacted with experimental condition: The increase in duration was more pronounced for shorter *z* strings.

Second, all four probability measures showed a significant word length effect. More importantly, the experimental manipulation had significant effects on both regression as well as skipping probability. When reading the *z* string version of the Potsdam Sentence Corpus, participants showed a considerably lower regression probability [$F(1,30) = 46.50$, $p = .000$]; this effect was stronger for shorter words (significant experimental manipulation × word length interaction [$F(10,21) = 2.67$, $p = .039$]). In addition, there was a significant effect of experimental manipulation on skipping probability [$F(1,30) = 5.34$, $p = .028$], and also a significant experimental manipulation × word length interaction [$F(10,21) = 5.42$, $p = .003$]. Interestingly, skipping rate is similar for 2- through 4-letter words (see Fig. 2.2d). For longer words, however, skipping probability is considerably lower in the normal reading as compared to the mindless reading condition. Apparently, long "real" words are harder to preprocess in the parafovea.

There was another significant interaction. While there was no significant effect of "experimental condition" on the probability of two fixations, a significant experimental condition × word length interaction could be observed [$F(10,21) = 5.22$, $p = .000$]: For short and medium long words, refixation probability was similar in both the mindless as well as the normal reading condition; however, for very long words (≥ 9 letters) refixation probability was lower in the mindless reading condition.

Given the high correlation between word length and word frequency, a similar pattern of results is observed when data are broken down by word frequency of the none-*z*-transformed words instead of word length (Appendix I, Table I3). There were, however, three deviating results. First, the main effect of experimental condition on skipping probability was not significant while the interaction with word length was preserved. Second, for regression probability the experimental condition × word frequency interaction was not significant. Third, the main effect of experimental condition on total reading time was significant [$F(1,30) = 6.05$, $p = .020$]. It appears that these differences are partly related to data power problems in the upper range of word lengths. For the present analyses, the Potsdam Sentence Corpus words were assigned to five word frequency classes but 11 word length categories; in addition, the corpus comprises relatively few words that are very long (cf., Sec. 2.1.3, p. 20).

2.2.2.2 Distributions of fixation durations and saccade lengths

Fig. 2.3 shows the frequency distribution for all fixation durations in the mindless reading and normal reading conditions. The proportion of fixation durations was analyzed for 20 levels (from 30 ms up to 600 ms in 30-ms steps). For each level of fixation duration, a one-factorial ANOVA repeated measures (mindless vs. normal reading) was carried out.

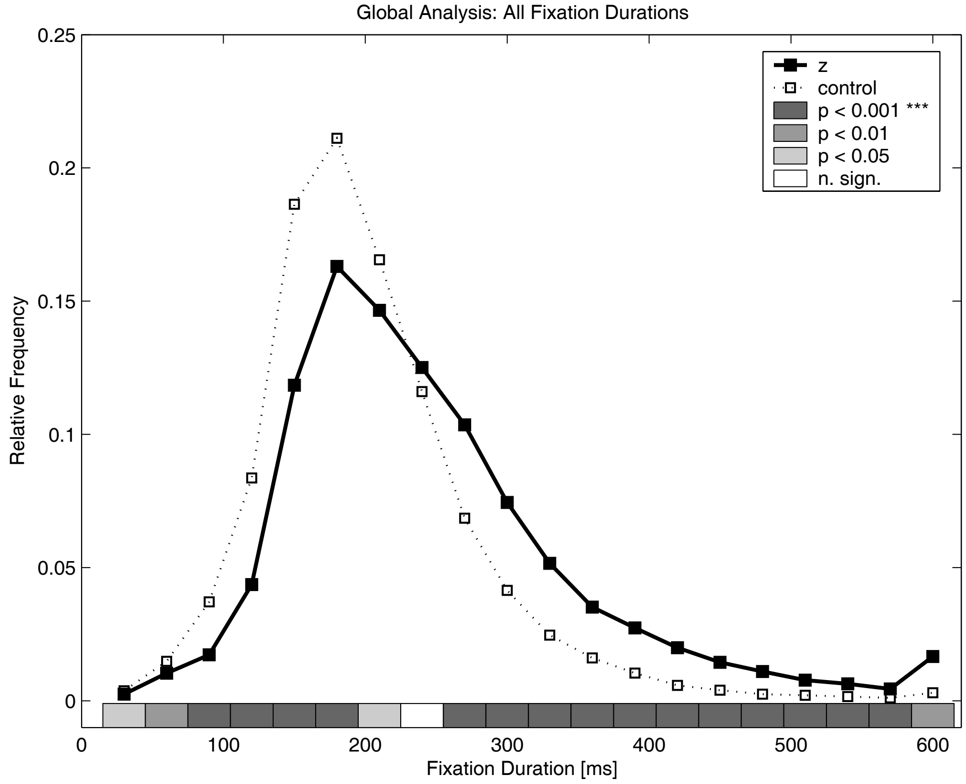

Fig. 2.3 Distribution of all observed fixation durations during *z* string "reading" (full squares) vs. normal reading (open squares). Fixation duration bins showing statistically significant differences in ANOVAs are highlighted along the *x*-axis. Areas in different shades of grey represent different levels of significance.

All fixation duration bins, except the bin representing fixation durations between 225 and 255 ms, yielded significant differences [$F(1,30) > 5.60$, $p \leq .025$]. Results on mean fixation durations are further supported by distributions for the four fixation duration measures: In agreement with the longer durations for the *z* string "reading" condition, we observe a right-ward shift for the corresponding distributions (Fig. 2.4). The means of the distributions for the *z* string data nicely reflect the well-known order of mean fixation durations – SFD > FIRSTFD > SECFD. Of further note from the figure is that the spread of the distribution for both first and second fixation durations is broader for *z* string "reading" as compared to normal reading data.

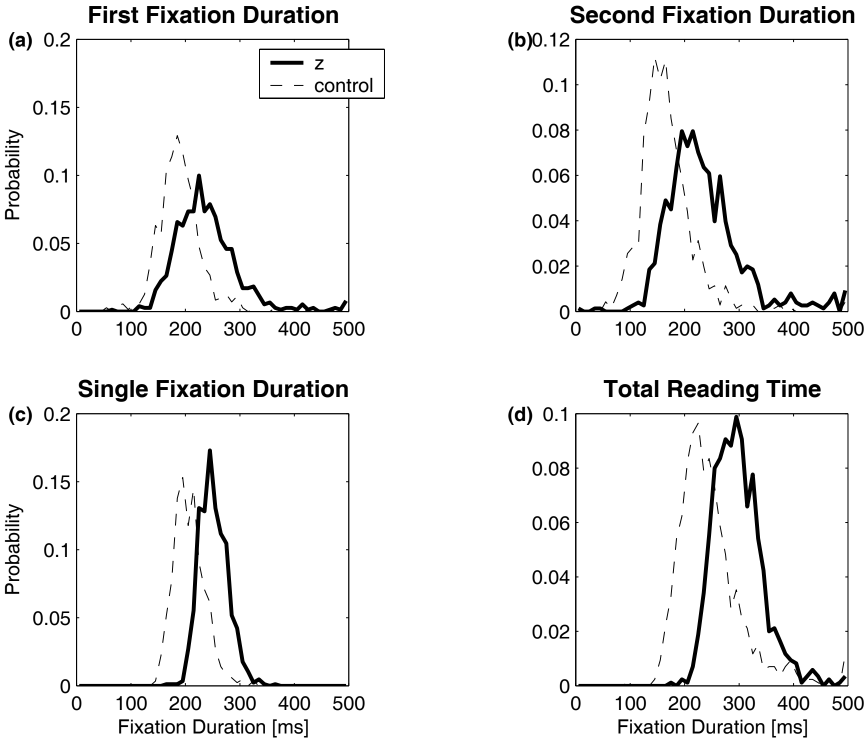

Fig. 2.4 Distributions of fixation durations. (a) Distributions of first fixation durations for experimental data and model simulations. (b) Second fixation durations. (c) Single fixation durations. (d) Total reading time. Solid line: experimental data; broken line: control data.

Finally, Fig. 2.5 shows the frequency distribution for all saccade lengths in mindless and normal reading conditions. Following Vitu *et al.* (1995) and Rayner & Fischer (1996), the proportion of saccade lengths was analyzed for 9 levels (from -17.5 letters, with the negative sign indicating regressions, up to 22.5 letters in 5-letter steps). Note that the figure actually shows more data points (in 1-letter increments). For each level of saccade lengths, a one-factorial ANOVA with experimental condition (*z* string "reading" vs. normal reading) as within-subject factor was carried out.

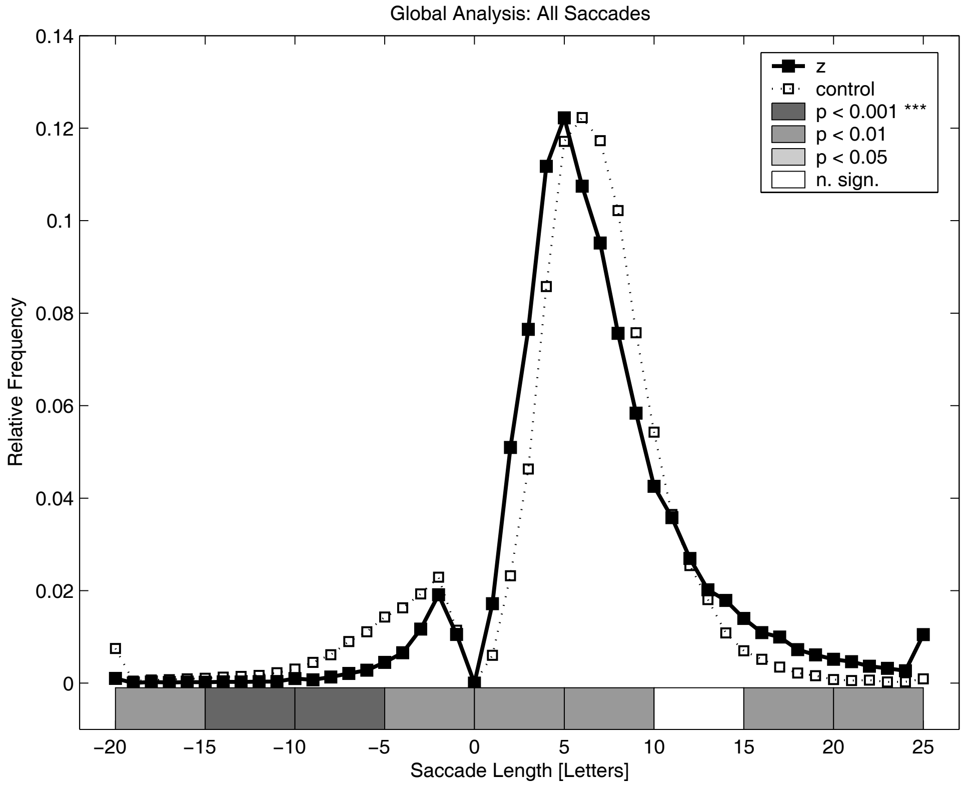

Fig. 2.5 Distribution of all observed saccade lengths during *z* string "reading" (full squares) vs. normal reading (open squares). Saccade length bins showing statistically significant differences in ANOVAs are highlighted along the *x*-axis. Areas in different shades of grey represent different levels of significance.

All saccade length bins, except where the distributions crossed (bin centered around 12.5 letters), yielded significant differences [$F(1,30) > 7.73$, $p \leq .007$]. When all saccade lengths of a given data sample are considered (and their binned relative frequencies thus sum up to 1), the distributions for mindless vs. normal reading deviate in several ways. First, there are fewer regressive saccades in the *z* string "reading" condition. This apparently holds for both long regressive saccades (inter-word regressions) and short regressive saccades (most of them being regressive refixations). In addition, the proportion of short forward saccades (1-5 letters) as well as very long forward saccades (≥ 15 letters) is higher when scanning *z* strings than when reading normal sentences; the opposite is true, however, for medium-long saccades. Roughly, this finding is compatible with the skipping rate being lower for short *z* strings (as opposed to short words) but higher for long *z* strings (see Fig. 2.2).

2.3 Experiment 3 – Reading with Salient OVP Experiment

Experiment 3 was inspired by visual search studies by Theeuwes and colleagues using the oculomotor capture paradigm (for a review on evidence regarding the relationship between attention and exogenous saccades in the oculomotor capture paradigm, see Godijn & Theeuwes, 2003). It is known that abrupt onsets have the ability to capture attention (independent of the goals of the observer) and also elicit exogenous (involuntary, stimulus-driven) saccades (Godijn & Theeuwes, 2003). Thus, automatic attentional capture is accompanied by oculomotor capture.

In Experiment 3, it was attempted to create a reading situation eliciting automatic oculomotor capture. For certain words of the Potsdam Sentence Corpus, the optimal landing letter was marked in red whereas the other letters were presented in black (see below). The red letters were expected to act as salient exogenous stimuli, to attract the eyes in terms of automatic oculomotor capture. Thus, participants were not explicitly prodded to the red-marked letters. However, different than in most of the studies using the oculomotor capture paradigm, the red letter did not have an abrupt onset; it is a static rather than a a dynamic salient exogenous stimulus.

It was predicted that means and standard deviations of landing position distributions might be influenced by this manipulation in a positive way. Ideally, means should be centered around OVP with the standard deviation of landing position distributions being considerably smaller than under normal reading conditions.

2.3.1 Participants, Apparatus, Materials and Procedure

Thirty-seven university students who responded to an advertisement at Potsdam University were recruited and consented to participate in the experiment. They received either course credit or a 5 € payment. All participants had normal or corrected-to-normal vision. One subject was excluded from all analyses because she generated valid data for less than 100 (out of 144) sentences. The remaining 36 subjects were 24 women and 11 men (mean age = 24.0 years, SD = 4.3 years; for one subject neither age nor sex information available). Detailed information on the age, sex, and eye dominance of participants as well as their performance in a measure of vocabulary and the digit symbol substitution test can be found in Appendix D. Participants were tested with an SR Research EyeLink II (500 Hz) system in the Golm-Lab.

In preparation of the experiment, word-based data from the original reading experiment (Exp. 1) were used. For each word of the Potsdam Sentence Corpus the probabilities for skipping (p_{SKIP}), and two fixations (p_2) were determined. The values were averages across the 65 participants reported in Kliegl *et al.* (2004). In addition, for every word length category, the 90th percentile (a percentile is a value on a scale of one hundred that indicates the percent of a distribution that is equal to or below it) for P0 and the 10th percentile for P2 were computed. For a word to be marked, its refixation probability had to be greater than the 10th percentile value of the appropriate word length category, whereas the skipping probability had to be smaller than the 90th percentile value of the appropriate word length category. Furthermore, only words being at least four letters long were marked since shorter words are often skipped. The first word in a sentence was never marked.

For every remaining word length category, the optimal landing letter was then computed by means of the refixation probability curves depicted in Fig. 3.1 (p. 63)[11] [word length 4 – letter 2; word length 5 – letter 3; word length 6 – letter 3; word length 7 – letter 4; word length 8 – letter 4; word length 9 – letter 5; word length 10+ – letter 5]. Words with more than 10 letters were treated like 10-letter words. Excluding the first word in the sentence, 569 out of 994 words were marked (57%). A complete list comprising the 144 sentences and their marked letters can be found in Appendix E.

2.3.2 Global Analyses

2.3.2.1 Four fixation duration and four probability measures

The control group for the reading with salient OVP experiment consisted of all university students from the original reading experiment (Exp. 1; n = 107, mean age = 22.26 years, SD = 3.55 years, range 18 to 38 years).

The overall impact of the experimental manipulation was evaluated by considering word-based summary statistics comprising four measures of fixation duration as well as four fixation probabilities, each measure being broken down by five logarithmic word-frequency classes (Fig. 2.6a and b; exact values for means and standard deviations in Appendix J, Table J1) and/or 11 word length categories (Fig. 2.6c and d; Appendix J, Table J2), respectively.

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[11] Restricted to 65 subjects, however, because Experiment 3 was designed in 2003.

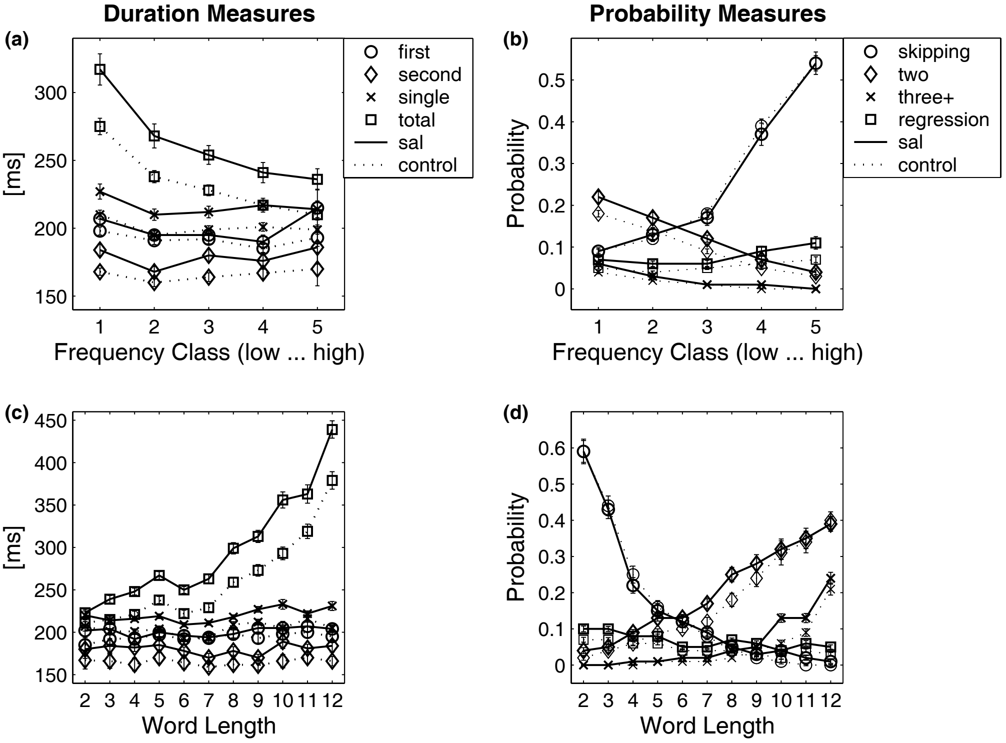

Fig. 2.6 Word-based summary statistics of different eye-movement measures by word frequency classes and by word length classes for reading with salient OVP data (*sal*) and normal reading control data. (a) Mean durations for first, second and single fixation durations and total reading time as a function of word frequency class. Results for experimental data are given by the solid line, while results obtained for control data are dotted. (b) Probabilities for skipping, two fixations, three or more fixations and the probability that a given word is the target of a regression as a function of word frequency class. (c) Mean durations for the same measures as in (a) as a function of word length class. (d) Probabilities as a function of word length class.

For each of the eight dependent measures (four durations, four probabilities), an ANOVA with "experimental condition" (reading with salient OVP vs. normal reading) as between-subject factor and "word frequency" and/or "word length" as the respective within-subject factor was employed. A complete report about the inferential statistics is provided in Appendix J, Table J3. In the following, significant effects for word-based means broken down by word frequency are highlighted.

Counter to expectation, when the OVP for certain words was marked in red, single fixation duration and total reading time are significantly inflated [SFD: *F*(1,141) = 6.63, *p* = .011; $\text{TIME}_{\text{TOTAL}}$: *F*(1,141) = 11.96, *p* = .001]. In addition, the probability of two fixations as well as the probability for three or more fixations are significantly increased [P_2: *F*(1,141) = 7.52, *p* = .007; P_{3+}: *F*(1,141) = 7.16, *p* = .008]. While refixation probability is affected, the duration of the first and second fixation on a word, however, are not affected by the experimental manipulation. Finally, we observe an increased regression probability [*F*(1,141) = 7.50, *p* = .007].

Thus, instead of facilitating the reading processing, marking the OVP of well-selected words of the Potsdam Sentence Corpus seemed to have a rather slightly disturbing effect.

2.3.2.2 Distributions of fixation durations and saccade lengths

Next, frequency distributions, based on all fixation durations, were examined (Fig. 2.7). The proportion of fixation durations was analyzed for 20 levels (from 30 ms up to 600 ms in 30-ms steps). For each level of fixation duration, a one-factorial ANOVA with experimental condition (reading with salient OVP vs. normal reading) was carried out.

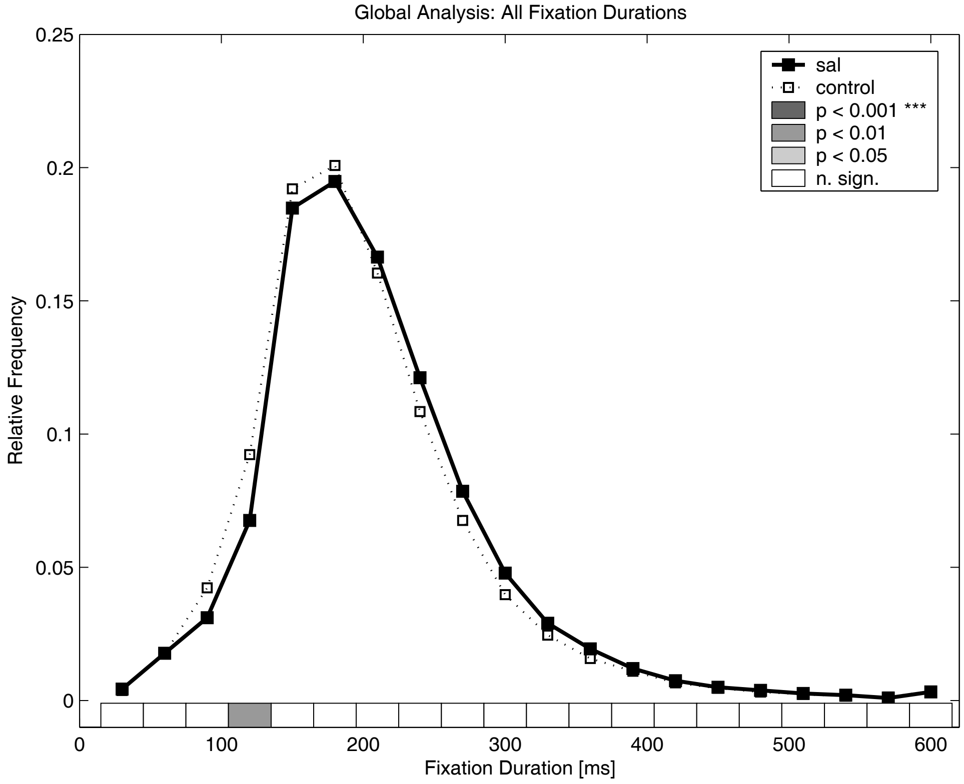

Fig. 2.7 Distribution of all observed fixation durations during reading with salient OVP (full squares) vs. normal reading (open squares). Fixation duration bins showing statistically significant differences in ANOVAs are highlighted along the *x*-axis. Areas in different shades of grey represent different levels of significance.

The only significant difference was found for the duration bin centered around 120 ms [*F*(1,142) = 8.578, *p* = .004]. At first glance, this result appears to contradict the finding of significantly inflated single fixation durations and total reading times in the reading with salient OVP condition (see Fig. 2.6). Note, however, that the distributions depicted in Fig. 2.7 were based on the durations of *all* fixations, except the first and last fixation in a sentence as well as fixations being shorter than 30 ms and longer than 1000 ms. Furthermore, word-based statistics had shown that the duration of the first and second fixation on a word were not affected by the experimental manipulation. Besides, increased total reading times simply reflect the higher refixation probability in the reading with salient OVP condition. Consequently, the distributions displayed in Fig. 2.7 can only reflect the effect of increased single fixation durations in the reading with salient OVP condition. Indeed, the effect appears to show as a slight right-ward shift of the distribution for the reading with salient OVP condition, even though the effect is not captured by the employed statistical analyses.

Finally, Fig. 2.8 shows the frequency distribution for saccade lengths in the reading with salient OVP and normal reading conditions. The figure shows data points in 1-letter increments. Again, the proportion of saccade lengths was analyzed for 9 levels (from -17.5 letters, with the negative sign indicating regressions, up to 22.5 letters in 5-letter steps). For each level of saccade lengths, a one-factorial ANOVA with experimental condition (reading with salient OVP vs. normal reading) as between-subject factor was carried out.

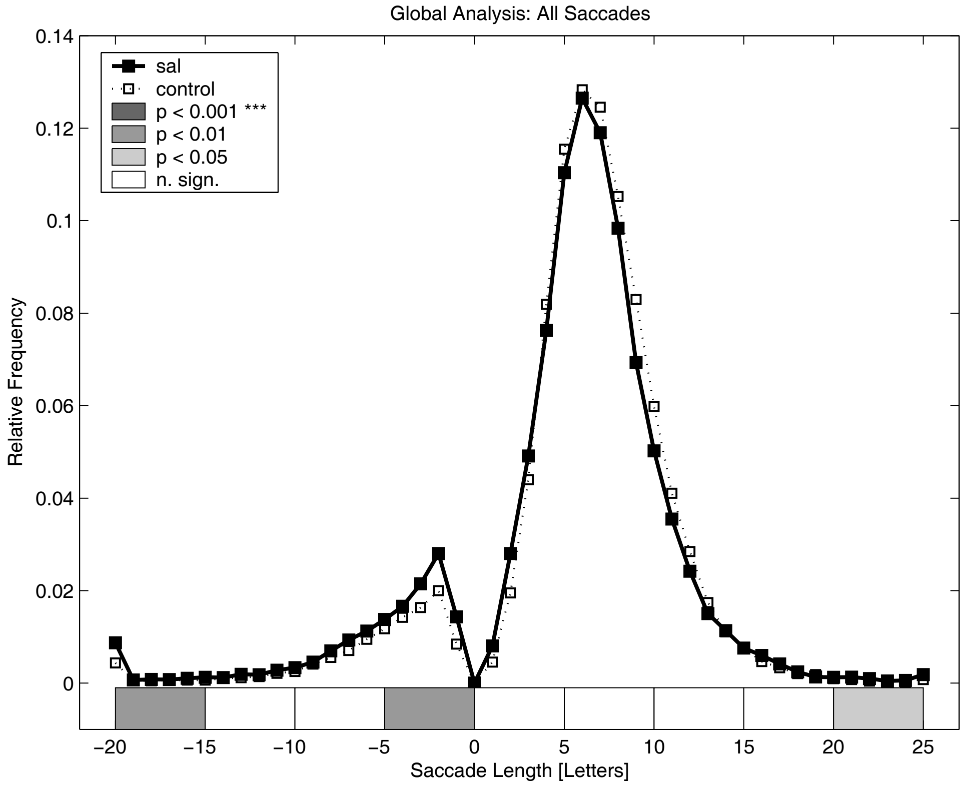

Fig. 2.8 Distribution of all observed saccade lengths during reading with salient OVP (full squares) vs. normal reading (open squares). Saccade length bins showing statistically significant differences in ANOVAs are highlighted along the *x*-axis. Areas in different shades of grey represent different levels of significance.

Of special note from Fig. 2.8 is that there is a larger proportion of short regressive saccades (-1 – -5 letters) when reading with salient OVP as opposed to normal reading, a finding which is compatible with the increased regression and refixation probability reported above.

2.4 Experiment 4 – Reading with a Bite Bar Experiment

Eye movements were collected with SR Research EyeLink systems. These eye trackers allow moderate head motion and thus do not require the use of a bite bar. However, rapid head or body movements can cause the headband to shift on the head, and also cause psychophysical gaze-position changes (EyeLink II, User Manual). Therefore, a chin rest was used for all experiments reported in this thesis, except in the current experiment.

Rather, in Exp. 4, participants read the sentences of the Potsdam Sentence Corpus with their heads fixed with a bite bar instead of being stabilized with a chin rest.

By employing this experimental manipulation, it should be examined if and to what extent an experimental setup which precluded any head movements influenced varying measures of eye-movement control in reading, compared to a less constrained viewing condition with a chin rest only. Such a comparison is related to the question how empirical results generalize across different laboratories. For example, laboratories working with a Dual-Purkinje Image eyetracker by default use a bite bar (and oftentimes also forehead restraints) to minimize head movements (e.g., Rayner *et al.*, 1996).

2.4.1 Participants, Apparatus, Materials and Procedure

Eighteen women and 13 men (mean age = 18.0 years, SD = 1.9 years) who responded advertisements at a high school in Potsdam were recruited and consented to participate in the experiment. Twenty-eight participants were high-school students, and three were university students. Thus, participants of Exp. 4 were comparatively young. They received a 5 € payment. All participants had normal or corrected-to-normal vision. Detailed information on the age, sex, and eye dominance of participants as well as their performance in a measure of vocabulary and the digit symbol substitution test can be found in Appendix F. The bite bar reading sample was tested with an SR Research EyeLink II (500 Hz) system in the Gutenberg-Lab.

2.4.2 Global Analyses

2.4.2.1 Four fixation duration and four probability measures

Most of the participants tested in the experiments were university students. In the current experiment, however, the great majority of participants were high-school students. Consequently, they were not contrasted with the 107 university students from Exp. 1 that served as a control group in experiments 3, 5, and 6. Rather, 31 age-matched control subjects were chosen from the subject pool of the original reading experiment (Exp. 1, see Sec. 2.1.1, p. 19). The control subjects were also high-school students having been tested in the Gutenberg-Lab with an SR Research EyeLink II (500 Hz) system. Remember that control subjects were tested with a chin rest.

The overall impact of the experimental manipulation was evaluated by considering word-based summary statistics comprising four measures of fixation duration as well as four fixation probabilities, each measure being broken down by five logarithmic word-frequency classes (Fig. 2.9a and b; exact values for means and standard deviations in Appendix K, Table K1) and/or 11 word length categories (Fig. 2.9c and d; Appendix K, Table K2), respectively.

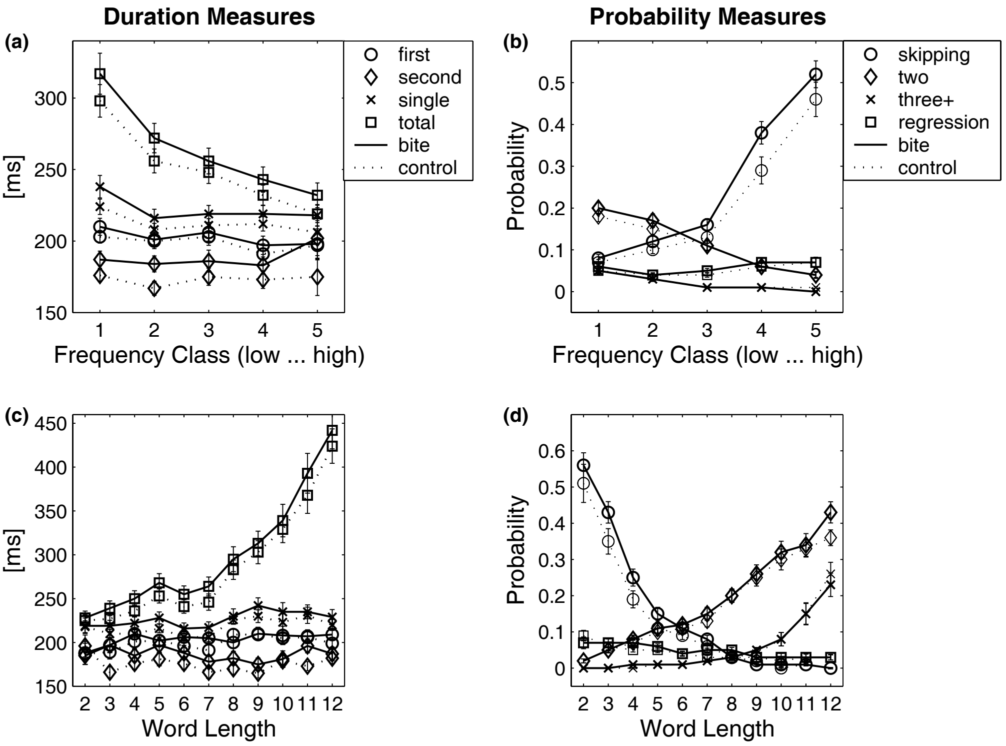

Fig. 2.9 Word-based summary statistics of different eye-movement measures by word frequency classes and by word length classes for reading with a bite bar data (*bite*) and chin rest reading control data. (a) Mean durations for first, second and single fixation durations and total reading time as a function of word frequency class. Results for experimental data are given by the solid line, while results obtained for control data are dotted. (b) Probabilities for skipping, two fixations, three or more fixations and the probability that a given word is the target of a regression as a function of word frequency class. (c) Mean durations for the same measures as in (a) as a function of word length class. (d) Probabilities as a function of word length class.

For each of the eight dependent measures (four durations, four probabilities), an ANOVA with “experimental condition” (reading with a bite bar vs. reading with a chin rest) as between-subject factor and “word frequency” and/or “word length” as the respective within-subject factor was employed.

There was only one significant effect of the experimental manipulation on any of the dependent measures: When data were broken down by word frequency, second fixation duration was longer when participants read with a bite bar as compared with a chin rest [$F(1,60) = 7.74$, $p = .008$]. The increased skipping probability, as suggested by Fig. 2.9b and Fig. 2.9d, just failed to be significant. A complete report about the inferential statistics is provided in Appendix K, Table K3.

2.4.2.2 Distributions of fixation durations and saccade lengths

The results reported above were further supported by the examination of fixation duration distributions, based on all durations. For none of the 20 duration bins significant differences were found for the two conditions contrasted [$F(1,61) < 2.42$, $p \geq .126$]. As for the spatial aspect of eye-movement patterns, results reported above were further corroborated by considering saccade length distributions. Only for the bin centered around -12.5 letters, a significant difference was found [$F(1,61) = 4.16$, $p = .046$] indicating a slightly higher proportion of long regressive saccades when participants' head was fixed with a bite bar.

2.5 Experiment 5 – Reading Under Low Contrast Experiment

In Exp. 5, it was investigated how a reduction of letter contrast influences eye-movement behavior: Participants read the sentences of the Potsdam Sentence Corpus with low letter contrast (10% of the normal resolution). This manipulation was expected to slow down reading while it should influence both the "when" as well as the "where" decision; thus, longer fixation durations and, roughly, shorter saccade lengths were expected. The latter should show in a decreased skipping probability, as well as in an increased refixation probability. In particular, reducing the visibility of the text should modulate the slope and vertical offset of the refixation OVP curve (see Sec. 3.2.4, p. 74).

2.5.1 Participants, Apparatus, Materials and Procedure

Thirty university students (27 women and 3 men, mean age = 22.6 years, SD = 2.9 years) who responded to an advertisement at Potsdam University were recruited and consented to participate in the experiment. They received either course credit or a 5 € payment. All participants had normal or corrected-to-normal vision. Detailed information on the age, sex, and eye dominance of participants as well as their performance in a measure of vocabulary and the digit symbol substitution test can be found in Appendix G. For participant-based statistics, 4 participants were excluded because they contributed less than 100 (out of 144) valid sentences. The low-contrast sample was tested with an SR Research EyeLink I (250 Hz) system.

2.5.2 Global Analyses

2.5.2.1 Four fixation duration and four probability measures

As in Experiment 3, the control group for the low contrast reading experiment consisted of all university students from the original reading experiment (Exp. 1; *n* = 107, mean age = 22.26 years, SD = 3.55 years, range 18 to 38 years).

The overall impact of the experimental manipulation was evaluated by considering word-based summary statistics comprising four measures of fixation duration as well as four fixation probabilities, each measure being broken down by five logarithmic word-frequency classes (Fig. 2.10a and b; exact values for means and standard deviations in Appendix L, Table L1) and/or 11 word length categories (Fig. 2.10c and d; Appendix L, Table L2), respectively.

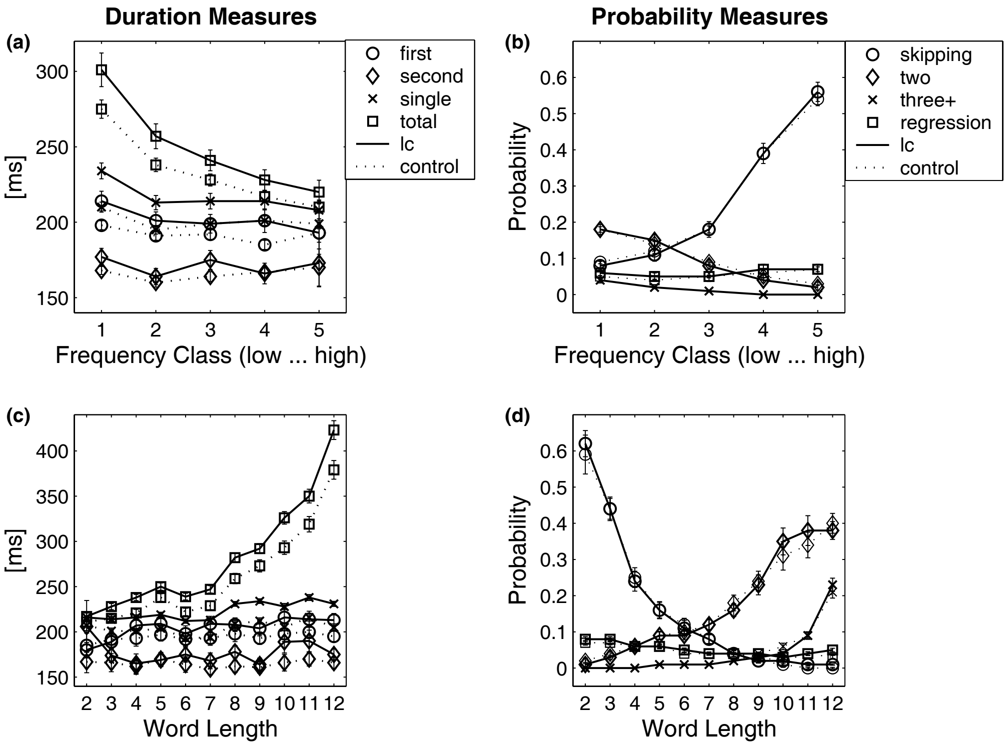

Fig. 2.10 Word-based summary statistics of different eye-movement measures by word frequency classes and by word length classes for low contrast reading data (*lc*) and normal reading control data. (a) Mean durations for first, second and single fixation durations and total reading time as a function of word frequency class. Results for experimental data are given by the solid line, while results obtained for control data are dotted. (b) Probabilities for skipping, two fixations, three or more fixations and the probability that a given word is the target of a regression as a function of word frequency class. (c) Mean durations for the same measures as in (a) as a function of word length class. (d) Probabilities as a function of word length class.

For each of the eight dependent measures (four durations, four probabilities), an ANOVA with "experimental condition" (reading with low contrast vs. normal reading) as between-subject factor and "word frequency" and/or "word length" as the respective within-subject factor was employed. A complete report about the inferential statistics is provided in Appendix L, Table L3. In the following, significant effects for word-based means broken down by word frequency are highlighted.

Processing a word with a single fixation is indicative of "undisturbed" processing of that word. Interestingly, in the low contrast reading condition single fixation duration is the only duration measure which is affected by the experimental manipulation: single fixation duration is significantly prolonged when letter resolution is decreased [word frequency: $F(1,131) = 5.74$, $p = .018$; word length: $F(1,131) = 7.39$, $p = .008$]. When data were broken down by word frequency, this effect was smaller for high-frequency words [experimental condition × word frequency interaction: $F(4,128) =$

4.42, $p = .009$]. In addition, there were also higher total reading times (Fig. 2.10a and c), but the effects failed to be significant.

Interestingly, the four probability measures, characterizing the spatial aspect of eye-movement behavior, were completely unaffected by the contrast manipulation.

2.5.2.2 Distributions of fixation durations and saccade lengths

Next, frequency distributions, based on all fixation durations, were examined (Fig. 2.11). Again, the proportion of fixation durations was analyzed for 20 levels (from 30 ms up to 600 ms in 30-ms steps). For each level of fixation duration, a one-factorial ANOVA (low contrast vs. control) was carried out yielding significant differences for all fixation durations between 120 and 330 ms, except 180 ms [$F(1, 132) > 4.13$, $p \leq .044$].

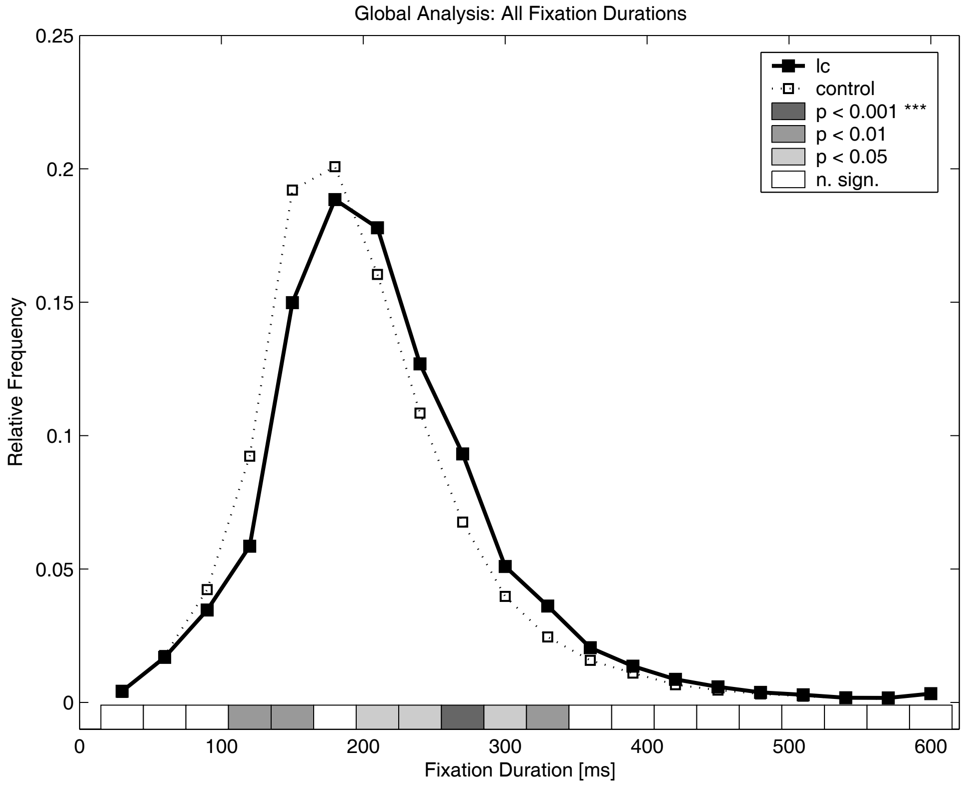

Fig. 2.11 Distribution of all observed fixation durations during reading with low letter contrast (full squares) vs. normal reading (open squares). Fixation duration bins showing statistically significant differences in ANOVAs are highlighted along the *x*-axis. Areas in different shades of grey represent different levels of significance.

When examining saccade length distributions, for none of the 9 saccade length bins significant differences were found [$F(1,132) < 1.11$, $p \geq .294$].

2.6 Experiment 6 – Reading Experiment with Saccade-Contingent Sentence Displacements Inducing Landing Position Errors

2.6.1 Theoretical Background

In Experiment 6, participants again read the sentences of the Potsdam Sentence Corpus. However, the whole sentence was displaced during saccades, inducing artificial landing position errors. In the experiment, the phenomenon of *saccadic suppression* (Matin, 1974) is exploited: During a saccade we do not obtain new information.

The motivation behind the experiment was threefold. First, other reading experiments using the Potsdam Sentence Corpus had shown that it is difficult to influence landing position distributions with more subtle manipulations, for example by reducing the letter contrast or marking the optimal viewing position of words. Therefore, now a very strong manipulation was chosen: By displacing the sentence during saccades, landing position errors were artificially induced. The interesting question to investigate was whether the sentence shifts, while they were not consciously perceived, induced specific oculomotor responses (for predictions, see Sec. 2.6.5.3.1, p. 56). The second question to be investigated is actually somewhat related to the first question: The experiment was also created to test the pre-programming hypothesis of refixation saccades (e.g., Beauvillain, Dukic, & Vergilino, 1999; Vergilino & Beauvillain, 2000; Vergilino-Perez & Beauvillain, 2004). Beauvillain and Vergilino argue for a pre-programming of refixation saccades with the initial saccade into the word. The present experiment bears resemblance to a double step experiment by Beauvillain, Dukic, & Vergilino (1999) in which letter strings of different lengths (7, 9, 11 letters) were displaced by one or two spaces in the same or opposite direction to that of the primary saccade. The shift was executed during the primary saccade into the item. Not surprisingly, initial landing position distributions were influenced by displacement condition. Distributions of refixation saccade amplitudes, however, did not vary as a function of shift condition. Refixation saccade amplitude was independent of initial landing position and thus did not correct the artificially induced fixation error. Based on that first study, the authors started to develop their refixation pre-programming notion (for details see Sec. 3.4.1, pp. 78). In the current experiment, the experimental setup used by Beauvillain *et al.* (1999) was transferred to a continuous reading situation. According to the pre-programming hypothesis, sentence displacements during initial saccades into words should not induce specific oculomotor responses (for detailed predictions, see Sec. 3.4.2, p. 80). Finally, the experiment was expected to be informative with regard to the origin of the Fixation-Duration IOVP effect (see Sec. 6.4, pp. 166).

Note that a first sentence-shift experiment had been carried out more than 20 years ago (O’Regan, 1981). In his study, a line of text was shifted during a saccade, either 3 letter spaces to the left or right respectively. While the study is only briefly mentioned in a book chapter, the reported results suggest that the sentence shifts had both spatial and temporal consequences on eye-movement behavior. When the line of text was shifted to the left, the probability of the following saccade being a regression was increased by about 33% as compared to a no-shift control condition. When the text was shifted to the right, there was no change in regression probability, as compared to the control condition, but mean saccade length and mean fixation duration were slightly reduced.

Only recently, findings from three similar reading experiments were presented at different conferences, but no comprehensive research reports are published yet. At a macro-level, all studies had the same goal: It was investigated whether the oculomotor system detects and responds to unexpected changes in landing position. At a micro-level, however, the theoretical focus was substantially different in each of the studies.

As the present experiment, the study by Huestegge, Radach, Vorstius, and Heller (2003) was designed to examine the metrics of refixation saccades with a more realistic sentence reading paradigm. During the initial saccade into a target word, the sentence was shifted either 1 or 2 letter spaces to the left or right respectively. Different than Beauvillain *et al.* (1999), they found that refixation saccade amplitude depended on initial landing position, in the metrics after the sentence shift. Thus, landing position errors were immediately corrected, a finding which they interpreted as being incompatible with a pre-programming of refixation saccades (but see Sec. 3.4.2, pp. 80 below). To determine the relevant visual-spatial reference system, in a second experiment a frame surrounding the text was shifted. Results showed that there was no effect of reference frame on saccadic responses.

Vitu, McConkie, & Yang (2003) set out for a replication of O’Regan’s (1981) original findings with a larger data set and more control conditions. Furthermore, they wanted to determine the origin of the shift-condition effect on regression probability. A number of predictions derived from three possible theoretical explanations (shift detection explanation, stimulus-based low-level visuomotor explanation, language processing explanation) were tested and rejected. It was proposed that the effect results from the position change of the line of text relative to the screen frame (but see Exp. 2 reported by Huestegge *et al.*, 2003).

Finally, Feng, Lee, Mazuaka, and Jincho (2005) compared eye movement programming in reading Japanese, Chinese, Korean, and English. Specifically, they examined whether saccades are aimed at specific words. If so, sentence shifts should increase corrective eye movements. Saccade length distributions for English and Korean data suggested that both follow a word-based strategy.

2.6.2 Participants, Apparatus, and Procedure

Participants. Forty-seven university students (36 women and 9 men, mean age = 23.3 years, SD = 4.8 years) who responded to an advertisement at Potsdam University were recruited and consented to participate in the experiment. They received either course credit or a 5 € payment. All participants had normal or corrected-to-normal vision. Detailed information on the age, sex, and eye dominance of participants as well as their performance in a measure of vocabulary and the digit symbol substitution test can be found in Appendix H, Table H1.

Apparatus, procedure, saccade-contingent sentence displacements. As participants read and their eye-movement data were being collected with a SR Research EyeLink II system, the presentation software package identified and counted saccades. An on-line algorithm based on velocity changes identified the beginning and end of each saccade. If the velocity value computed for the current checkable data sample, see below, exceeded a threshold of 30 deg/second, the algorithm signaled the detection of a saccade.

Critical for the present experiment were the sentence displacements. They were very obvious to onlookers, of course, for whom the changes were usually occurring during fixations rather than during saccades. For readers, however, sentences were displaced during saccades, exploiting the fact that we cannot take up new visual information during saccades. Of course, this required the sentence displacement to be finished before the end of a given saccade.

Since the duration of reading saccades is rather short (20-40 ms, see Fig. 1.1, p. 10), the current laboratory setup included several sources of delay that had to be identified and controlled for. First, the SR Research EyeLink II system has a system delay which can be reduced to 3 ms by using the "pupil only mode" and turning off the "heuristic filtering" feature. Second, a further 2 sample (= 4 ms) delay had to be accepted because data were smoothed for velocity computation. Eye positions were transformed to velocities with a weighted moving average of velocities over five data samples [*n*-2, *n*-1, *n*, *n*+1, *n*+2] to suppress noise. While *n*+2 is the current data sample from the Ethernet link, *n* is the current checkable sample, thus introducing a 2-sample delay. A third and major delay factor was related to the refresh rate of the monitor used for sentence presentation. Given a refresh rate of 120 Hz, the one-line sentence was refreshed every 8.3 ms. Note that vertically, the sentence was presented at the middle of the screen. Generally put, to minimize the delay introduced by the monitor, it was implemented that saccades starting at an unfavorable time within the monitor refresh cycle were not used as displacement saccades. Fourth, MATLAB is slow; it required up to 6 ms to read the data from the Ethernet link, to run the computations and to actually displace the sentence. Consequently, the total delay between the beginning of a saccade and the sentence displacement could easily add up to about 20 ms. For data from the original reading experiment (Exp. 1), mean saccade duration amounted to 32 ms. Therefore, the delay faced in the current experiment is critical for very short (in terms of both duration and amplitude, since both measures are highly correlated) saccades. Thus, there were instances where readers could have perceived the sentence shifts. However, only 3 readers reported that they sometimes noticed something irregular while reading (Appendix H, Table H2). To technically control for that issue, messages were sent to an output file to indicate on-line detected beginnings and ends of saccades. A message was also sent when a sentence displacement was finished. From these data it could be reconstructed whether participants could have seen the sentence displacements or not. However, following the data collection the raw data were reanalyzed to identify the beginnings and ends of saccades more precisely by using a saccade detection algorithm developed by Engbert & Kliegl (2003b). In that way, online saccade detection was validated offline.

2.6.3 Design

There were four displacement conditions: The sentence was either shifted 2.5 letters to the left, 1 letter to the left, 1 letter to the right, or 2.5 letters to the right. For every displacement saccade, displacement condition was assigned randomly. However, if the displacement value would make the sentence disappear to the right or left of the screen, the algebraic sign of the chosen displacement value was reversed (e.g., from -2.5 letters to +2.5 letters). The first saccade in a sentence was never a displacement saccade. Only every other saccade could be a displacement saccade. Thus, the saccade following a displacement saccade was never a displacement saccade itself. In addition, the maximal number of displacements in the sentence was determined by sentence length: number of words divided by two, plus 1 (in case of even number of words) or 1.5 (in case of uneven number of words). For example, in a 7-word sentence, a maximum of 5 sentence displacements could occur. During practice sentences, no saccade-contingent sentence displacements took place.

2.6.4 Terminology

Most analyses presented below focus on the *fixation* following a displacement saccade as well as the *saccade* following a displacement saccade; they are termed as *critical fixation* and/or *critical saccade* respectively.

With regard to the sentence displacements, three types of saccades occurred in the experiment. First, there were saccades during which the sentence was displaced (*displacement saccades*: 38% of all saccades in the experiment). Second, there were saccades following a displacement saccade (*critical saccades*: 38% of all saccades in the experiment). It is important to note that such a saccade was never a displacement saccade itself. In that way, it could be investigated how the critical saccade responds to the preceding sentence shift. Third, the remaining saccades were “normal” saccades; they were neither used for sentence displacements nor preceded by a displacement saccade (24% of all saccades in the experiment). Due to the design of the sentence displacements, however, 45% (n = 6334) of these “normal” saccades were first saccades in a sentence. Consequently, the design of the current experiment did not include a reliable no-shift control condition.

When data from Exp. 6 are considered, two types of coordinates and/ or metrics are distinguished: *After*-shift coordinates represent the word and within-word position the saccade landed on, and *before*-shift coordinates represent the word and within-word position the saccade *would* have landed on without the saccade-contingent sentence displacement.

2.6.5 Global Analyses

2.6.5.1 Characteristics of the four shift conditions

In total, 38% of all saccades generated by 47 participants in this experiment were displacement saccades (*n* = 21,745); 86% of them were inter- or intra-word *forward* saccades. Because displacement condition was assigned randomly to a selected saccade during the experiment, displacement saccades were evenly distributed across the four shift conditions: -2.5 letters: 24.56%, -1 letter: 24.77%, +1 letter: 25.23%, +2.5 letters: 25.44%.

The mean SR Research EyeLink II system delay was 4.0 ms (average across 47 participants, see Appendix H, Table H2). The proportion of saccades where the sentence displacement could be finished before the online detected end of the saccade, was on average 96% (range: 89.7%-99.5%, see Appendix H, Table H2). Cases where the shift could have been seen were excluded from analyses.

In the majority of cases, the saccade-contingent sentence shift led to a landing error *within* the word the eyes would have landed on if there hadn't been a sentence shift. However, 22% of all displacement saccades led to the fixation of a different word. This finding was further explored by computing the proportion of within- vs. between-word overshoots and/ or undershoots as a function of shift condition and word length (Fig. 2.12, Table 2.1). In this context, *overshoot* and *undershoot* are defined relative to the location the eyes would have landed on if there had not been a sentence shift. Note that the terms "landing error" and "over-/ undershoot" are not quite correct, because the sentence shift could actually improve (and thus not only impair) the landing position situation. On the one hand, a sentence shift could potentially correct a within-word undershoot or overshoot by bringing the eyes (closer) to the center of the word. On the other hand, a between-word landing shift could potentially correct what would have been a mislocated fixation (cf., Fig. 6.2, p. 145).

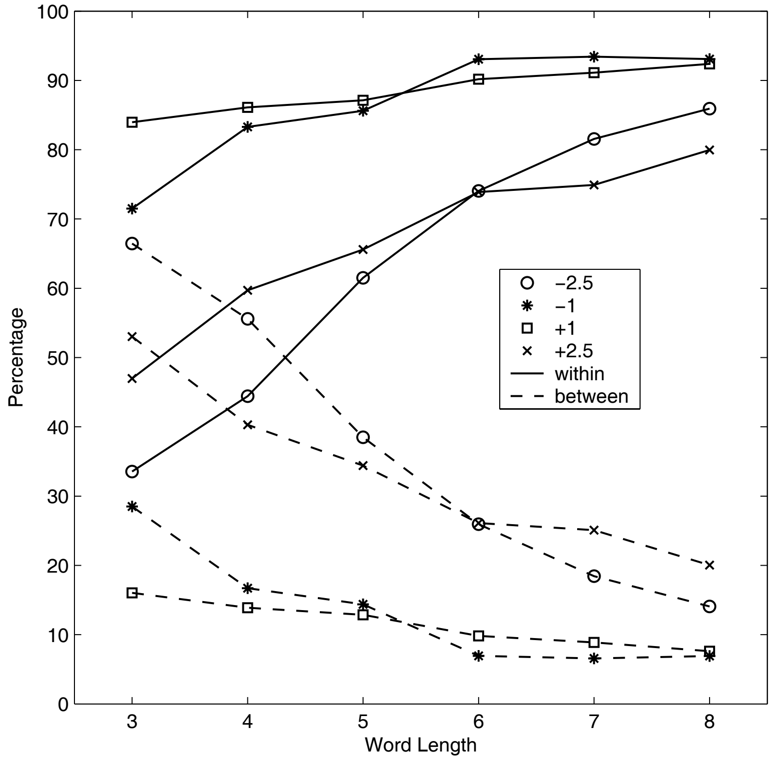

Fig. 2.12 Reading with recurrent sentence shifts experiment. Percentages of within-word vs. between-word landing shifts as a function of shift condition and word length.

Table 2.1 Reading with recurrent sentence shifts experiment. Percentages of within- vs. between-word overshoots and/ or undershoots as a function of shift condition and word length.

Shift Cond.	**-2.5 Letters**		**-1 Letter**		**+1 Letter**		**+2.5 Letters**	
Word Length	**Within-**	**Between-**	**Within-**	**Between-**	**Within-**	**Between-**	**Within-**	**Between-**
	Word Overshoot		**Word Overshoot**		**Word Undershoot**		**Word Undershoot**	
3	34	66	72	28	84	16	47	53
4	44	56	83	17	86	14	60	40
5	62	38	86	14	87	13	66	34
6	74	26	93	7	90	10	74	26
7	82	18	93	7	91	9	75	25
8	86	14	93	7	92	8	80	20
All Word Lengths	67	33	87	13	89	11	69	31

Analyses revealed that for every shift condition, within-word landing shifts (Fig. 2.12, straight lines) were more frequent than between-word landing shifts (broken lines). Of course, 2.5-letter shifts – in either direction – induced more between-word landing shifts than 1-letter shifts. With increasing word length, there is an increasing probability that the sentence shift results into a within-word shift, as opposed to a between-word shift. Thus, between-word landing shifts are more frequent with short words. Note that for short words, landing position distributions are generally close to the end of the word (see Chapter 4, pp. 100). Therefore, if the sentence shift was initiated during a saccade to a short word, a (2.5-letter) *left*-shift more frequently led to a *between*-word landing shift, as opposed to a within-word landing shift, than a (2.5-letter) *right*-shift.

2.6.5.2 Analyses based on all fixations, compared with normal reading data

Most analyses related to the current experiment will examine readers' oculomotor responses to the four saccade-contingent sentence displacement conditions, in global and detailed analyses (cf., Sec. 2.6.5.3). The following global analyses, however, aim at providing an overall impression of the impact of the experimental manipulation. Data from the reading with recurrent sentence shifts experiment were contrasted with normal reading control data. As in Experiments 3 and 5, all university students from the original reading experiment served as the control group (Exp. 1; *n* = 107, mean age = 22.26 years, SD = 3.55 years, range 18 to 38 years). In a first set of analyses, it was tested whether fixation durations and saccade lengths were globally affected when reading was manipulated with recurrent sentence shifts. Analyses were based on all fixations and saccades.[12] Thus, as far as the sentence shift data were concerned, all three types of fixations and/or saccades[13] were jointly considered and contrasted with normal reading data.

First, the proportion of fixation durations was analyzed for 20 levels (Fig. 2.13). For each level of fixation duration, a one-factorial ANOVA (reading with sentence shifts vs. control) was carried out. The only significant difference was found for the duration bin centered around 180 ms [$F(1,153) = 6.267$, $p = .013$].

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[12] However, first and last fixations in a sentence as well as fixations being shorter than 30 ms and longer than 1000 ms were excluded.

[13] Displacement saccades, critical saccades, remaining saccades; see above.

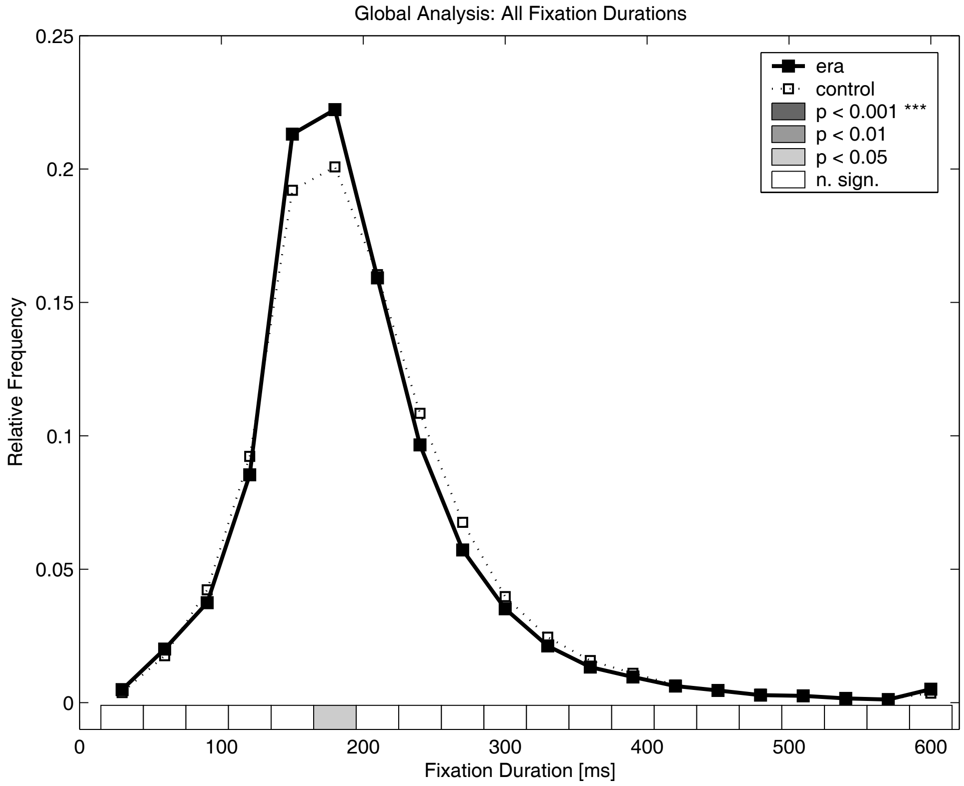

Fig. 2.13 Distribution of all observed fixation durations during reading with recurrent sentence shifts (full squares) vs. normal reading (open squares). Fixation duration bins showing statistically significant differences in ANOVAs are highlighted along the *x*-axis. Areas in different shades of grey represent different levels of significance.

Next, as an overall test of the spatial aspect of eye-movement patterns, Fig. 2.14 shows the frequency distribution for saccade lengths in the reading with recurrent sentence shifts and normal reading conditions. Data from the sentence shift experiment were not so much different than normal reading control data. Note that the sentence shift data will be explored in detail when the effect of sentence shift on saccade length distributions is investigated (see Sec. 3.4.3.1.2 & Sec. 3.4.3.1.3, pp. 85).

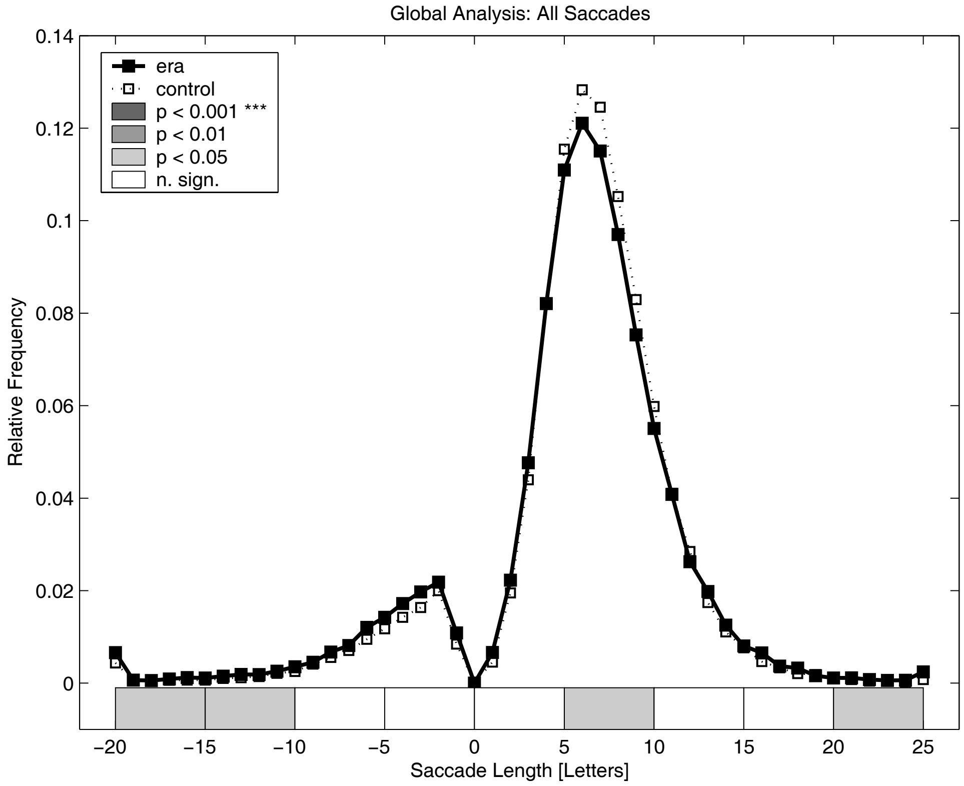

Fig. 2.14 Distribution of all observed saccade lengths during reading with recurrent sentence shifts (full squares) vs. normal reading (open squares).

Interestingly, the proportion of very long progressive as well as regressive saccades was significantly increased in the sentence shift reading experiment as compared to normal reading control data. In reading, very long regressive saccades indicate that participants went back to the beginning (region) of the sentence to reread a great part of the sentence.

To further explore the overall impact of the experimental manipulation, two trial-based measures were computed. For a given trial the mean number of fixations (Fig. 2.15a) and/or the mean sentence reading time (Fig. 2.15b) were computed. A trial corresponds to a sentence to be read. Actually, both measures depend on word characteristics of the sentence (e.g., number of words). However, since the 144 sentences of the Potsdam Sentence Corpus were always presented in random order, the two trial-based measures should not be systematically affected. Both measures, which are actually correlated, were obtained by averaging data across subjects.

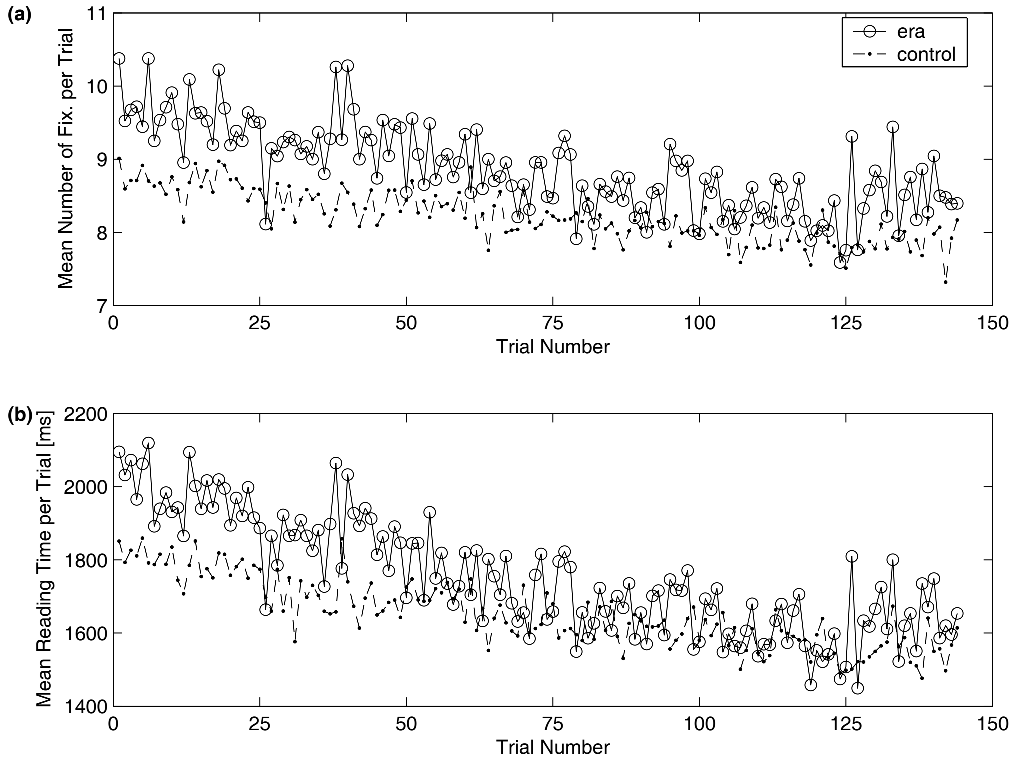

Fig. 2.15 Reading with recurrent sentence shifts experiment. (a) Mean number of fixations across trials. (b) Mean Sentence reading time across trials.

An examination of Fig. 2.15 indicates two findings. First, readers usually invested somewhat more time – measured in number of fixations and/or sentence reading time – when reading with recurrent sentence shifts, due to an increased refixation and regression probability (cf., Table 3.2, p. 83). Second, throughout the experiment, both measures exhibited a decreasing trend which was more pronounced for the reading with recurrent sentence shifts condition. Roughly, changes were in the order of one fixation and/or 200 ms only.

2.6.5.3 Analyses based on saccades and/ or fixations after sentence-shift saccades

The most interesting aspect of the current experiment is to investigate how the oculomotor system responds to saccade-contingent sentence displacements. Related analyses will be presented within the following three chapters. Chapter 3 covers the optimal viewing position in reading. In continuous reading, the OVP is derived from refixation probability curves. Therefore, analyses related to the refixation pre-programming hypothesis will be presented in Sec. 3.4 (pp. 78). In Chapter 4, the preferred viewing location phenomenon which is derived from landing position distributions is discussed. Consequently, in Sec. 4.4.5 (pp. 114) it will be shown how sentence displacements affected landing position distributions computed for displacement saccades (validity check of the experimental manipulation) and/or the critical saccades following the displacement saccades. Finally, in Sec. 6.4 (pp. 166) it will be discussed how sentence displacements affect the Fixation-Duration IOVP effect.

For all these analyses, only sentence shifts during *forward* saccades were considered. In this case, a *right* shift translates into a *same*-direction shift whereas a *left* shift corresponds to an *opposite*-direction shift (cf., Beauvillain *et al.*, 1999). Unfortunately, due to the design of the present study, data from the four shift conditions could not be compared with data from a 0-letter control condition where the sentence was simply replaced by itself (as, for example, in Vitu *et al.*, 2003).

To test oculomotor responses to saccade-contingent sentence displacements, the saccade and/or fixation *following* the displacement saccade will be considered. For some analyses of these *critical saccades*, the *displacement saccades* were used as a control. It was assumed that properties of the displacement saccade (amplitude, peak velocity, duration) itself were not affected by the fact that sentence displacements were realized during these saccades. Indeed, saccade length distributions (Fig. 3.14b, p. 86) as well as investigations of the so-called *main sequence* (not presented) supported this assumption. Therefore, because of the lack of a 0-letter shift control condition, the displacement saccades served as a control condition when, for example, saccade length distributions were considered. For the *critical fixations*, however, there was no reliable control condition available.

2.6.5.3.1 Predictions regarding oculomotor responses to sentence shifts

At a macro-level, the present experiment was created to investigate whether the oculomotor system detects and responds to unexpected changes in landing position (see Sec. 2.6.1, p. 45). Specific predictions about how the eyes might respond to experimentally induced landing shifts can be derived by contrasting landing position distributions in before-shift vs. after-shift coordinates. Theoretically, these predictions are tied to the more general assumption that saccade targeting is word-based, with the center of the word as the optimal landing position (see introductory comments on Chapter 4, p. 100). When landing position distributions for displacement saccades are computed according to the *before*-shift coordinates (Fig. 2.16), we observe the preferred viewing location phenomenon (see Chapter 4, pp. 100): The maximum of landing position curves is close to word center; for longer words, there is a tendency to undershoot the center of the word as the optimal landing position.

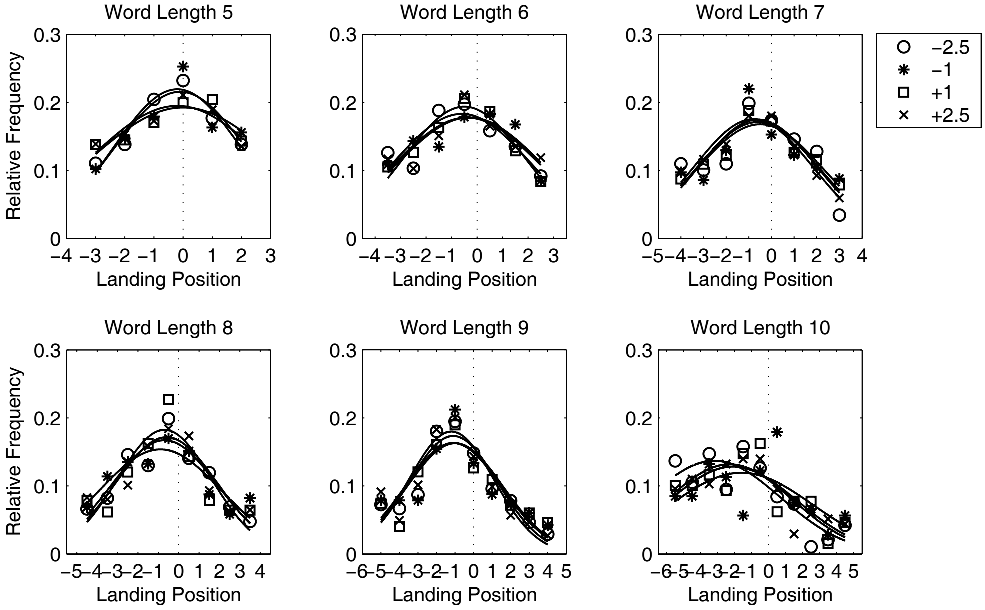

Fig. 2.16 Reading with recurrent sentence shifts experiment. Landing position distributions for sentence-shift saccades as a function of word length and shift condition. Both within-word as well as between-word landing shifts are jointly considered. Computations are based on *before*-shift coordinates. Each panel represents data for a given word length (5 through 10).

For *within*-word landing shifts, a number of predictions can be derived: A 2.5-letter left-shift leads to an overshoot of the OVP (see Fig. 4.12, pp. 115). It is therefore predicted that the eyes respond to that interference with an increased probability of regressive intra-word saccades. A 1-letter left-shift, however, on average brings the eyes closer to the OVP and thus improves the landing position situation; apparently, in this case there is no need for a corrective response. Artificially induced within-word landing-shifts to the right, on the other hand, aggravate the undershoot tendency of the eyes. Especially for the 2.5-letter right-shift condition, it is hypothesized that the eyes might correct the severe undershoot with forward refixations.

Between-word landing shifts result into experimentally induced mislocated fixations. On the one hand, between-word *over*shoots caused by *left*-shifts will lead to unintended skippings and/ or failed refixations (cf., Fig. 6.2, p. 145, for cases of mislocated fixations). It is hypothesized that between-word overshoots caused by left-shifts might be corrected by inter-word regressions. On the other hand, between-word *under*shoots caused by *right*-shifts will lead to unintended refixations and/ or failed skipping. Interestingly, SWIFT simulations exploring responses to "real" mislocated fixations (Sec. 6.3.2.2, pp. 159) showed that in case of a failed skipping the virtual eyes primarily responded with a skipping of the next word(s) or simply a forward saccade to the next word (Fig. 6.11, p. 161).

For detailed predictions regarding the refixation saccade pre-programming hypothesis, it is referred to Sec. 3.4.2 (p. 80).

2.7 Summary of Global Analyses

The results of word-based statistics across experiments are compiled in Table 2.2.

Table 2.2 Summary of word-based statistics across experiments. For a given experiment, the impact of the experimental manipulation (EXP) as well as the influence of word frequency (FREQ) and/ or word length (WL) was investigated. Eight dependent measures of eye-movement behavior – four fixation duration measures and four probability measures – were considered. Significant effects are symbolized by “+” signs.

		FIRSTFD	**SECFD**	**SFD**	**TIME**$_{\text{TOTAL}}$	p_{SKIP}	p_2	p_{3+}	p_{REGR}
		EXP							
EXP. 2	**FREQ**	+	+	+	+				+
Z	**WL**	+	+	+	+				+
EXP. 3	**FREQ**			+	+		+	+	+
SAL	**WL**		+	+	+			+	+
EXP. 4	**FREQ**		+						
BITE	**WL**								
EXP. 5	**FREQ**			+					
LC	**WL**			+					
		EXP × FREQ/ WL							
EXP. 2	**FREQ**			+	+	+	+		
Z	**WL**			+	+	+	+		+
EXP. 3	**FREQ**				+			+	
SAL	**WL**				+				
EXP. 4	**FREQ**								
BITE	**WL**								
EXP. 5	**FREQ**			+					
LC	**WL**								
		FREQ/ WL							
EXP. 2	**FREQ**			+	+	+	+	+	+
Z	**WL**			+	+	+	+	+	+
EXP. 3	**FREQ**	+		+	+	+	+	+	+
SAL	**WL**	+		+	+	+	+	+	+
EXP. 4	**FREQ**	+		+	+	+	+	+	+
BITE	**WL**			+	+	+	+	+	+
EXP. 5	**FREQ**	+		+	+	+	+	+	+
LC	**WL**	+		+	+	+	+	+	+

Taking out higher-level lexical, semantic, or syntactic processes involved in reading (Exp. 2) clearly had the strongest impact on eye-movement behavior. When participants read a *z* string version of the Potsdam Sentence Corpus, as compared to the normal version, they produced considerably longer fixation durations and shorter forward saccades. Actually, the finding of prolonged fixation durations is opposite to what one would expect, given a task without word processing demands. One possible explanation is that participants, when mimicking reading in the mindless reading condition, simply overestimated the time they spend at each fixation during normal reading (Vitu *et al.*, 1995). It appears, however, questionable as to whether participants are able to consciously influence their eye movements in such an experiment. Also, the finding of prolonged fixation durations is compatible with results from isolated word recognition paradigms (e.g., Vergilino-Perez, Collins, & Dore-Mazars, 2004) and visual search tasks where we usually observe higher fixation durations than in continuous reading. Apparently, in continuous reading the eyes are pulled by semantic parafoveal information. Moreover, the finding of a decreased regression probability in the mindless reading condition can be explained by the lacking semantics and syntax.

Marking the OVP of certain words (Exp. 3) turned out not to facilitate reading. It actually increased single fixation durations, as well as refixation probability and consequently total reading time; it also elicited more inter-word regressive saccades. Reduction of letter contrast (Exp. 5) led to increased single fixation durations while probability measures where not at all affected. This finding is a good argument in favor of the independence of "when" and "where" decisions in reading (cf., Sec. 1.2, p. 11). Basically, using a bite bar instead of a chin rest (Exp. 4) had no impact on eye-movement behavior as captured by word-based statistics.

Interestingly, there was always an effect of word length and/ or word frequency on any of the four probability measures, sometimes interacting with the experimental manipulation effect. Furthermore, the present experiments provide information about refixation behavior, as reflected in first and second fixation duration; the results will be discussed in context (see Sec. 8.3.2, pp. 223).

It is important to point out a limitation related to the word-based summary statistics (Kliegl *et al.*, 2004). Separate ANOVAs were carried out for several measures of fixation duration and probability. Even though first and single fixation duration were defined as non-overlapping measures, there are still correlations between the four duration measures. Most blatantly, single fixation duration, first fixation duration and second fixation duration contribute to total reading time. In addition, there are dependencies between the four probability measures.[14] Strictly speaking, such dependencies prevent separate analyses for the eight measures. It was still opted for the present analysis framework because it represents most of the measures used in the reading research community. In perspective, a coherent framework of non-redundant,

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[14] When adding the probability of single fixation, the five probability measures sum up to one.

independently defined dependent measures would be desirable. Furthermore, statistical methods other than ANOVAs, for example hierarchical models, might capture the effects even more adequately.

We now turn from global analyses to more fine-grained analyses. In the following three chapters, three landing-position dependent phenomena are introduced. First, the optimal viewing position (OVP) is introduced (Chapter 3). Second, it is shown that the eyes do not always land at the OVP, creating the difference between the optimal and the preferred viewing location (PVL, Chapter 4). Third, it is investigated how fixation durations vary as a function of landing position (Chapter 5). From a cognitive view on eye-movement control in reading it is predicted that word center as the OVP would appear to be the best place to fixate and process a word. However, empirical data show that fixation duration is highest, not lowest, when fixating near word center. In Chapter 6, these Fixation-Duration IOVP effects will be explained as a consequence of mislocated fixations caused by saccadic errors; thus, IOVP effects will be linked to PVL curves.

3 The Optimal Viewing Position (OVP)

While the *preferred* viewing location (see Chapter 4, pp. 100) reflects where readers do land in a word, the *optimal* viewing position (OVP)[15] designates the optimal fixation position within a word. The optimal fixation position for processing a word was originally derived from word identification curves in the isolated word presentation paradigm: The OVP is defined as the location in a word at which recognition time is minimized. According to O'Regan and Lévy-Schoen (1987), the OVP is slightly left of the center of the word. Due to the rapid drop of visual acuity with distance from the center of the fovea, the letters of a word are most rapidly identified when the eyes are near the word's center. The consequences of making fixations at locations other than the OVP have been extensively studied (for a review, Rayner, 1998). Most importantly, a *refixation OVP effect* was consistently found (e.g., O'Regan & Lévy-Schoen, 1987): The frequency of refixating a word (that is, of making an additional fixation after the initial fixation on the word) is lowest when the eyes initially fixate the center of the word. The refixation OVP effect generalizes to continuous reading (McConkie *et al.*, 1989; Rayner & Fischer, 1996; Rayner *et al.*, 1996; Vitu, O'Regan, & Mittau, 1990; Vitu, 1991c; Vitu *et al.*, 2001) and coincides with the OVP determined by word identification times. Therefore, most cognitive and oculomotor models assume that, with their initial saccade, readers target the word center, i.e. the optimal viewing position (e.g., McConkie *et al.*, 1988; Reichle *et al.*, 1999, 2003; but see Vitu, 2003, proposing that the eyes move forward with no specific saccade target).

3.1 Refixation OVP Effect

To investigate the optimal viewing position, for words of differing lengths the refixation probability was computed as a function of initial landing position (Fig. 3.1a). Depicted is the fraction of initial fixations at different letter positions on words of lengths 3 through 8 that were immediately followed by a refixation on the word. Data were collapsed across all participants and all words of a given length. The curves are relatively smooth due to the large sample size (*N* = 245) and the considerable number of words (a corpus of 944 words). Consistent with prior reports (e.g., McConkie *et al.*, 1989; Vitu *et al.*, 1990; Rayner *et al.*, 1996), participants were much more likely to

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[15] The phenomenon was originally termed "convenient viewing position" by O'Regan (1981).

refixate a word if they initially landed on the beginning or end of the word than if they landed near its middle.

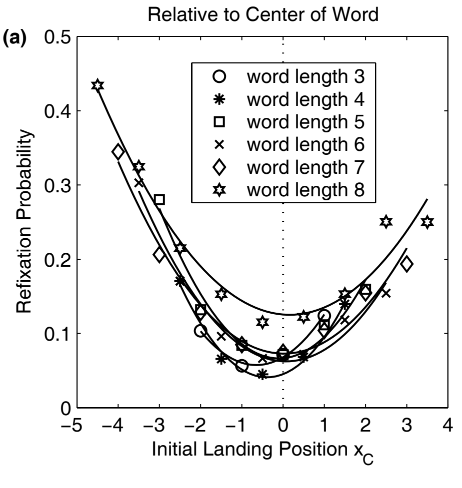

Fig. 3.1 Mean refixation probability as a function of the initial landing position within a word, for 3- to 8-letter words. (a) The initial landing position in the word is plotted as letter position relative to the center of the word. For words of a given length, the leftmost position corresponds to the space to the left of the word. (b) Landing position is standardized. In both panels, the dotted vertical line represents the center of the word.

Following McConkie *et al.* (1989), the refixation curves depicted in Fig. 3.1 were fitted to a quadratic polynomial, i.e.

$$y = A + B(x - C)^2, \quad (1)$$

where x denotes the initial fixation position and y is the refixation probability. In Eq. (1), C reflects the fixation position within a word where refixation probability is minimal and thus indicates the OVP. Parameter A indicates the actual refixation probability at OVP. Mathematically, A and C reflect the vertical and/or horizontal offset of the curve, respectively. B is the slope of the parabolic curve; it represents how refixation probability increases with deviation from OVP, that is B quantifies the penalty paid for not fixating at OVP. To obtain estimates for these three parameters characterizing the refixation probability curve, a grid search method with a minimum-χ^2 criterion was applied. Best-fitting lines for word lengths from 3 to 8 are shown in Fig. 3.1. Numerical values for the three free parameters in Eq. (1) as well as for CC as the center-based C value are given in Table 3.1. Note that word length itself is a confounding factor for the shape of refixation curves presented in Fig. 3.1a. The curve for a long word necessarily consists of more data points and covers a broader range of fixation positions than the curve for a short word. Therefore, the original (non-centered) landing position axis (e.g., ranging from 0 to 4 letters for 4-letter words) was standardized by dividing the landing positions by the length of the word (Fig. 3.1b), leading to landing positions ranging between 0 and 1 (for example 0, 0.25, 0.5, 0.75, 1.0 in the example). In Eq. (1), *x* was substituted for *x’=x/L*, where *L* denotes word length. This substitution was compensated by a transformation of parameters *B* and *C* to $B' = B \cdot L^2$ and *C’* = *C*/*L*. The transformed values for *B’* and *C’* are also listed in Table 3.1. Parameter *A* was not affected by these transformations. Interestingly, the behavior of parameter *B’* changed with the transformation: Whereas the absolute value of *B* decreased across word lengths, *B’* systematically increased.

Table 3.1 Quadratic fit to refixation probability curves: Estimates of parameters *A*, *B* and *C*.

Word Length	Center of Word	Parameters						χ^2	Total *N*	Number of Refixations
		A	*B*	*B’*	*C*	*CC*	*C’*			
3	2	0.058	0.025	0.225	1.35	-0.65	0.45	0	24497	2182
4	2.5	0.041	0.028	0.448	2.11	-0.39	0.53	0.0002	18251	1645
5	3	0.066	0.024	0.6	2.9	-0.1	0.58	0.001	21550	2750
6	3.5	0.062	0.018	0.648	3.57	0.07	0.6	0.001	19532	2466
7	4	0.073	0.016	0.784	4.02	0.02	0.57	0.0015	17619	2572
8	4.5	0.125	0.014	0.896	4.66	0.16	0.58	0.004	13149	2734

Note. *CC* = *C* - Center of Word, χ^2 denotes sum of squared residuals.

Fig. 3.2 visually depicts the parameters collected in Table 3.1; in addition, the present data set is compared with data reported by McConkie *et al.* (1989). The word length effect on *B'* was captured by fitting linear regression functions to the data. Following Vitu *et al.* (2001), in the present analyses parameter *C* was center-based by applying $CC = C - (L/2 + 0.5)$. McConkie *et al.* (1989), however, used a slightly different transformation: $CC = C - (L/2 + 1)$.

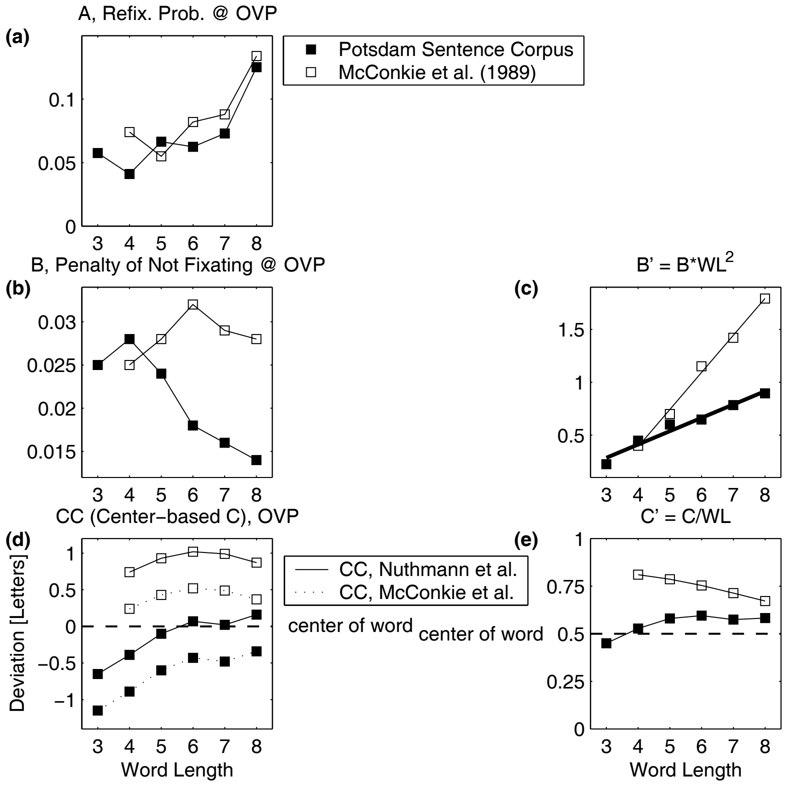

Fig. 3.2 Quadratic fit to refixation probability curves, comparison of Potsdam Sentence Corpus data (full squares) with data reported by McConkie *et al.* (1989, open squares): Parameters *A* (panel a), *B* (panel b), *B'* (panel c), center-based *C* (panel d), and *C'* (panel e) as a function of word length.

For the minimum point of the refixation curve, i.e., parameter *A*, there is a tendency to increase with word length (Fig. 3.2a). In this respect, the German data are in good agreement with the English data. Furthermore, McConkie *et al.* (1989) reported that, except for four-letter words, there is no influence of word length on parameter *B*, the slope parameter; their data are replotted in Fig. 3.2b. They denote this finding as "unexpected" (p. 251). However, when standardized for word length, both the German and the English data show a positive linear relationship between *B'* and word length (Fig. 3.2c). This indicates that the penalty of not fixating at OVP increases with word length. For German words of lengths 3 to 8, the OVP, as reflected in parameter *C*, was at the center or up to 2/3 character positions to the *left* of the center of the word (Fig. 3.2d).[16] Interestingly, for English data McConkie *et al.* (1989) found the OVP to be ¼ to ½ character position to the *right* of the center of the word (Fig. 3.2d), dotted line with open squares). It turned out that a factor contributing to this notable difference between the two data sets is the age of the participants tested. For young readers, OVP is right of

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[16] Note that the difference between panel (d) and (e) is caused by the different ways of defining word center.

word center while for old readers, OVP is left of word center with the difference being about one letter (see Nuthmann *et al.*, in prep.). However, for either data set the deviations from word center were small. Therefore, it is concluded that the center of the word is the optimal viewing position.

3.2 Influence of Experimental Manipulations on Parameters of the OVP Function

In the current section, the influence of experimental manipulations on the three parameters of the quadratic OVP function is investigated. A limiting factor for these analyses is the fact that refixations are not very frequent. For example, in the original reading experiment (Exp. 1, $N = 245$), 16% of all saccades were refixation saccades. In addition, the data provided by a given participant stem from a maximum of 144 sentences. Therefore, the subject-based refixation probability curves per word length were usually not stable enough to show the characteristic parabolic shape. Consequently, individual data were not fit to a quadratic function, and no statistical analyses were undertaken. Rather, data presented in this section are descriptive and were obtained by simply averaging across all participants.

3.2.1 Results from *Z* String “Reading” Experiment (Exp. 2)

The *z* string “reading” experiment demonstrates that the quadratic refixation behavior is also present if there are no word identification demands (Fig. 3.3). There are, however, notable differences. Roughly, initial fixations left of word center are more frequently followed by a refixation when readers scanned the *z* version of the Potsdam Sentence Corpus as compared to the normal version. Interestingly, the opposite is true when the initial fixation occurred right of word center.

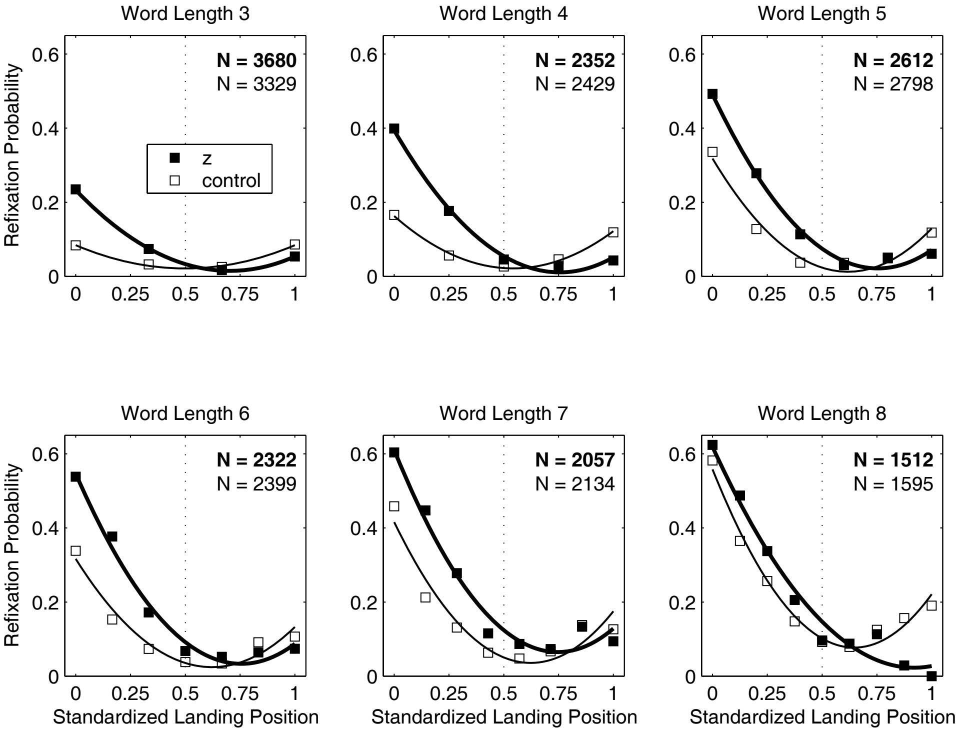

Fig. 3.3 Refixation probability curves, comparison of *z* string "reading" (full squares) with "normal" reading control data (open squares) as a function of word length. Each panel represents data for a given word length (3 through 8). Also presented is the best fit to $y = A + B(x - C)^2$.

To ease interpretation of the results, Fig. 3.4 visually depicts the parameters of the quadratic OVP function as a function of word length, contrasting *z* string "reading" data with normal reading control data (descriptive statistics: Appendix M, Table M1).

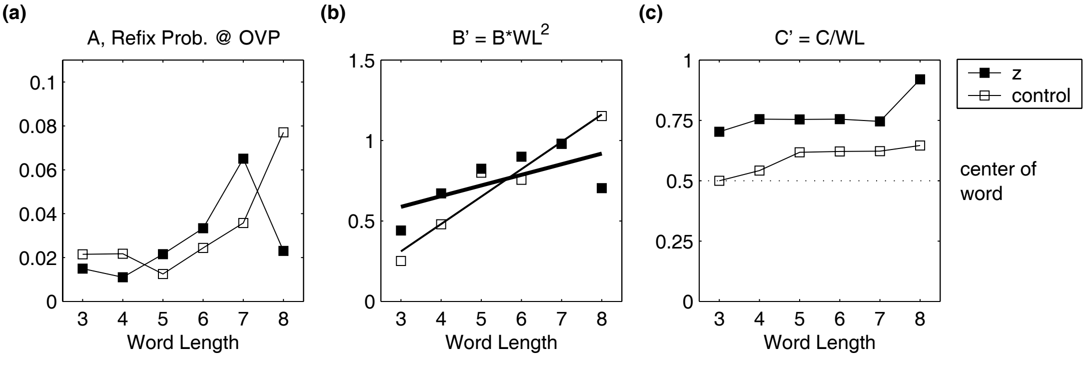

Fig. 3.4 Quadratic fit to refixation curves, comparison of *z* string "reading" data (full squares) with "normal" reading control data (open squares): Parameters *A* (panel a), *B'* (panel b), and *C'* (panel c) as a function of word length.

While the data for parameters *A*, and *B'* do not show very systematic patterns, the most striking aspect of the data presented in Fig. 3.4 is that the OVP, as reflected in parameter *C'*, is systematically and considerably shifted to the right for the *z* string "reading" data (Fig. 3.4c). In this specific aspect, the data are inconsistent with findings by Vitu *et al.* (1995) who reported very similar refixation probability curves for meaningless letter strings as compared to real words. The data are more consistent, however, with data reported by Rayner & Fischer (1996). In three reading conditions, they had participants read 80 one-line sentences, once as normal text, containing a target word of high or low frequency, and once as *z*-transformed text. As for refixation probability curves, they reported systematic differences when the initial fixation occurred at the *end* of the target word. In this specific case, readers were much less inclined to refixate if the target was a *z* string than if it was a high-frequency or low-frequency word (target length 6 and 7)[17]. To allow statistical analyses, they used Vitu *et al.*'s (1995) zoning algorithm to categorize the initial landing position into beginning, middle, or end of a word. Only for the end zone, the three target types differed significantly from one another. They concluded that the failure to identify a word from a perceptually sub-optimal viewing position induces a refixation in that word. Furthermore, they argued "Importantly, the same deviation from an OVP induced fewer refixations in a meaningless string. This difference illustrates the importance of lexical processing demands for the spatial aspect of oculomotor control and shows that visual factors alone cannot account for the eyes' behavior during reading" (p. 742).

However, the following analyses on the direction of the refixation saccade (progressive vs. regressive) will show that this strong conclusion needs to be reconsidered. The proportion of progressive vs. regressive refixations is 86:14 for *z* string "reading" data while it is about 70:30 for university students in normal reading (Exp. 1, $n = 107$). Fig. 3.5 further explores this difference in that it plots the proportion of refixations as a function of direction, word length, and initial landing position within word. Thus, the data presented in Fig. 3.5 are standardized in a way, that – for a given sample of reading data – *all* refixation cases sum up to 100%. Left vs. right panels display data for progressive vs. regressive refixations, respectively; the different shades of gray symbolize different word lengths. For regressive refixations, data presentation is aligned to the last letter of the word with the maximum analyzed word length, thus landing letter 8. For shorter words, consequently, data are presented in the bins from

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[17] For target length 5, however, not only *z*-strings but also high-frequency words showed a decreased refixation probability if the initial fixation was at the end of the target.

[max. wl – wl] until [max. wl] (e.g., regressive refixations on 3-letter words are collected in bins 5-8).

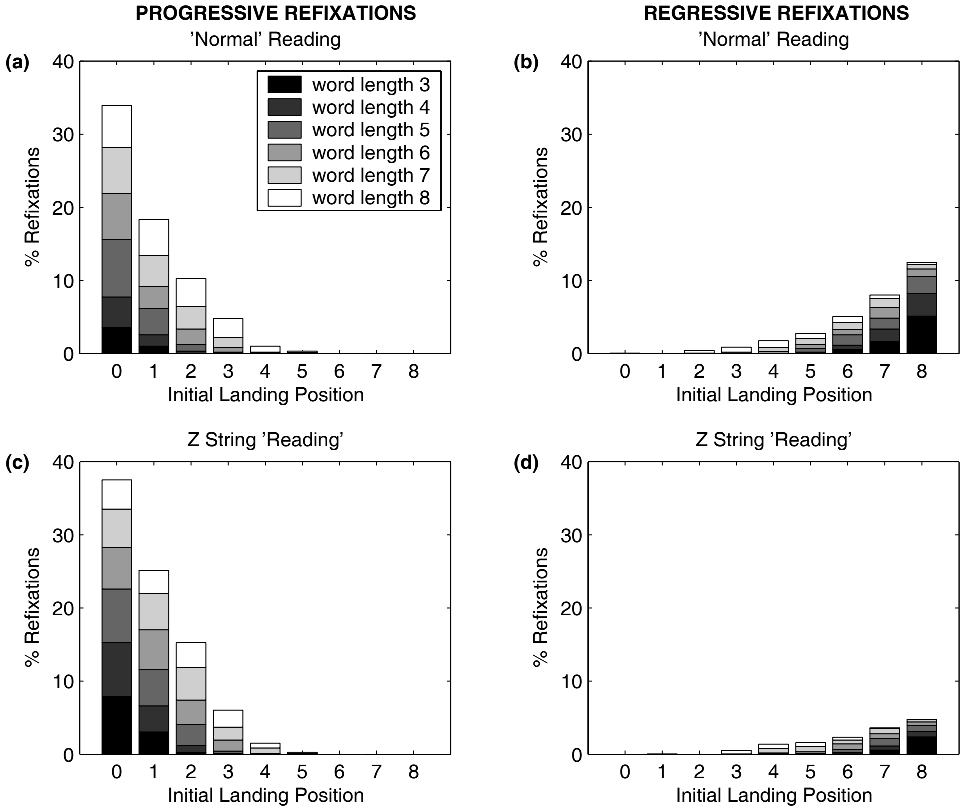

Fig. 3.5 Proportion of refixations as a function of direction (progressive vs. regressive), word length and initial landing position within the word; first row: normal reading data, second row: *z* string "reading" data; left panels: progressive refixations, right panels: regressive refixations.

A comparison of left vs. right panels reveals three findings. First, relative to all refixations, regressive refixations are notably less frequent in the *z* string "reading" condition than in the normal reading condition. Second, in both experimental conditions most progressive refixations are launched from near word beginning, while most regressive refixations are launched from the end of a word. Third, the analysis uncovers the new and somewhat counterintuitive finding that most regressive refixations are initiated from the last letter of 3-letter words. More generally put, regressive refixations are associated with short rather than long words. For progressive refixations, on the other hand, there is no apparent word length effect.

Since the second finding is relevant for the current question, it is further specified by investigating the direction of refixation saccades as a function of word length and – more importantly – center-based initial landing position within word (Fig. 3.6).

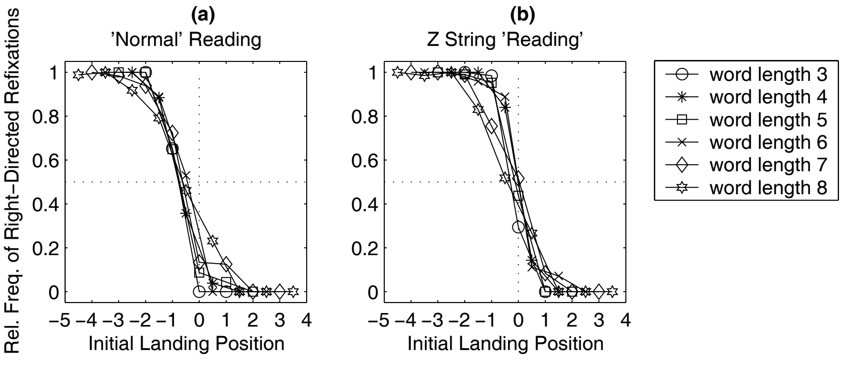

Fig. 3.6 Direction of refixation saccades as a function of word length and – more importantly – center-based initial landing position within word: (a) "normal" reading data vs. (b) *z* string "reading" data.

The analysis reveals that most regressive (left-directed) refixation saccades are initiated right of word center while most progressive refixation saccades are initiated left of word center. This observation can be related to Rayner & Fischer's (1996) finding of a reduced refixation probability for *z* strings as opposed to real words when the initial fixation occurred at the end of the target – this result is in all likelihood associated with a reduced frequency of regressive refixations in the *z* string "reading" condition.

For the present *z* string "reading" experiment, the reduced frequency of regressive refixations – which are predominantly initiated right of word center – translates into a rightward shift of the OVP (Fig. 3.3, Fig. 3.4c). Also, word-based statistics had revealed that the probability of inter-word regressions is extremely low for *z* string "reading" data (Fig. 2.2, p. 28). The *z* string "reading" experiment was set up as an oculomotor control condition without ongoing word identification demands. Therefore, the results on both intra-word and inter-word regressive saccades lend support to the assumption that both types of saccades are strongly related to word identification.

3.2.2 Results from Reading with Salient OVP Experiment (Exp. 3)

Experiment 3 aimed at the experimental manipulation of oculomotor errors. It was reasoned that marking the OVP of certain words might reduce the variance of landing position distributions and hence reduce overall refixation probability. However, global analyses already revealed that word-based refixation probability, as a function of word frequency and/ or word length, was higher when the OVP of well-selected words was presented in red as compared to normal reading with all words and letters presented in black (Sec. 2.3.2.1, p. 34).

In the current analysis, the specific influence of initial landing position on refixation probability was examined (Fig. 3.7). Analyses were based on fixations on all words, i.e., not only on fixations on words with salient OVP.

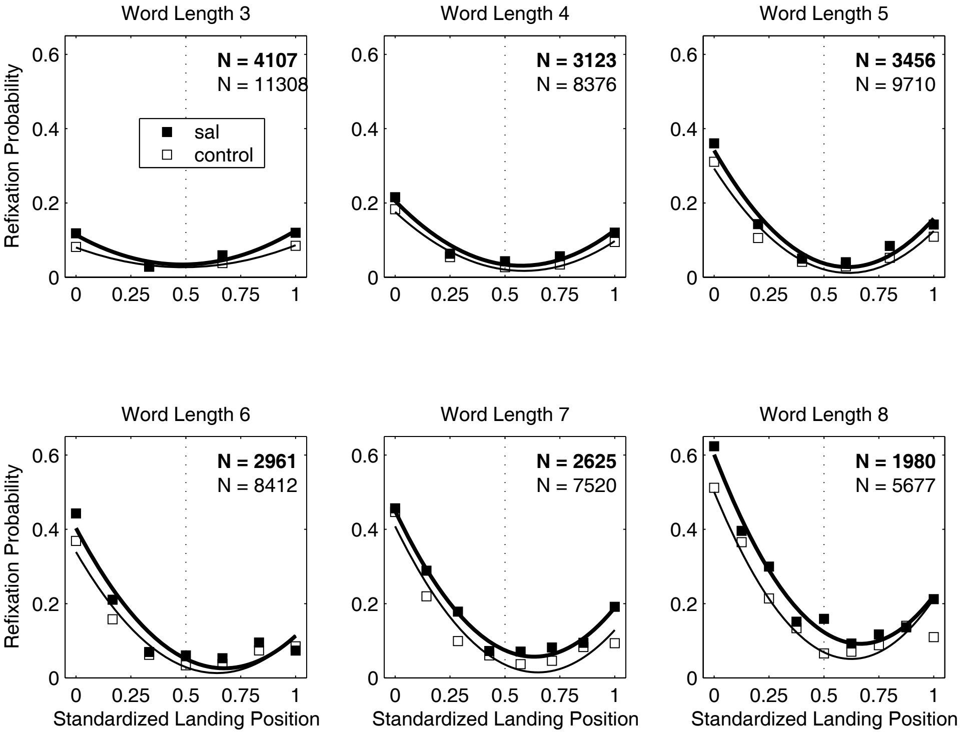

Fig. 3.7 Refixation probability curves, comparison of reading with salient OVP data (full squares) with normal reading control data (open squares) as a function of word length. Each panel represents data for a given word length (3 through 8). Also presented is the best fit to $y = A + B(x - C)^2$.

Fig. 3.8 visually depicts the parameters of the quadratic OVP function as a function of word length, contrasting reading with salient OVP data with normal reading control data (descriptive statistics: Appendix M, Table M2).

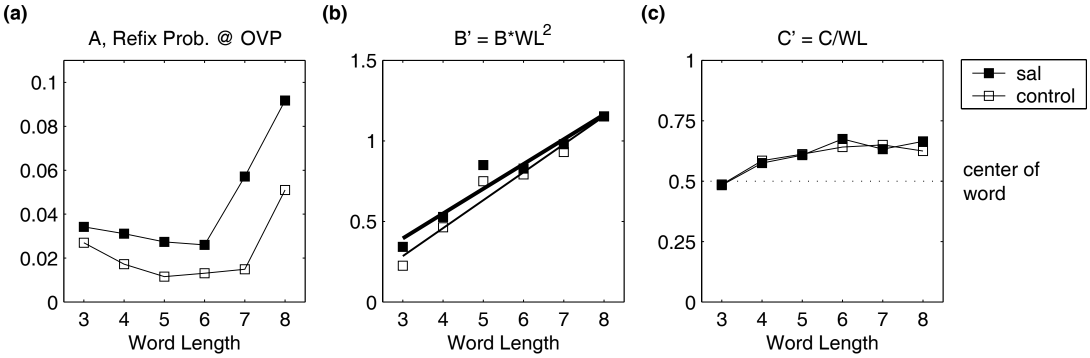

Fig. 3.8 Quadratic fit to refixation curves, comparison of reading with salient OVP data (full squares) with normal reading control data (open squares): Parameters *A* (panel a), *B'* (panel b), and *C'* (panel c) as a function of word length.

The OVP (parameters *C'*) is clearly unaffected by the reading with salient OVP manipulation (Fig. 3.8c). Likewise, the penalty of not fixating at OVP (as reflected in *B'*) appears to be unaffected (Fig. 3.8b). The maximum of the refixation probability curve (*A*), however, is increased when the OVP of well-selected words was marked in red (Fig. 3.8a). Given the lacking effects on *B'* and *C'*, this translates into a vertical upward displacement of the refixation probability curves.

3.2.3 Results from Reading with a Bite Bar Experiment (Exp. 4)

Next, the influence of initial landing position on refixation probability was examined for a sample of readers whose head was fixed with a bite bar. They were compared with age-matched participants from Exp. 1 where the head was stabilized with a chin rest (Fig. 3.9).

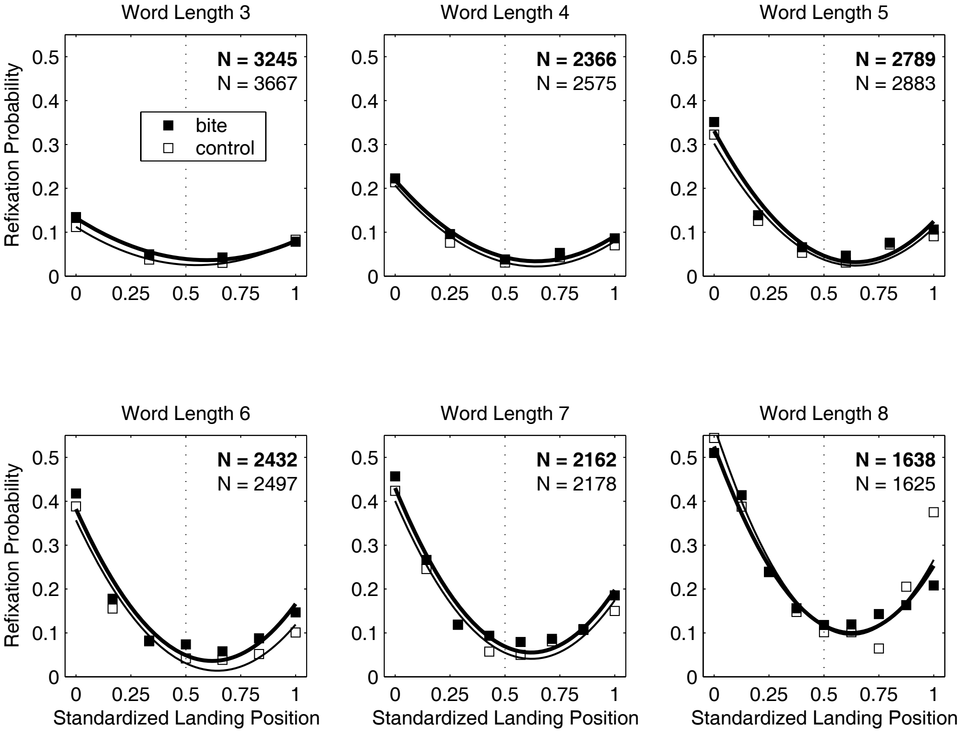

Fig. 3.9 Refixation probability curves, reading with a bite bar data (full squares) vs. chin rest reading control data (open squares) as a function of word length. Each panel represents data for a given word length (3 through 8). Also presented is the best fit to $y = A + B(x - C)^2$.

Parameters *B’* and *C’* were completely unaffected by the use of a bite bar instead of a chin rest (Fig. 3.10; descriptive statistics: Appendix M, Table M3). Parameter *A*, however, is slightly increased when participants’ head was fixed with a bite bar (Fig. 3.10a).

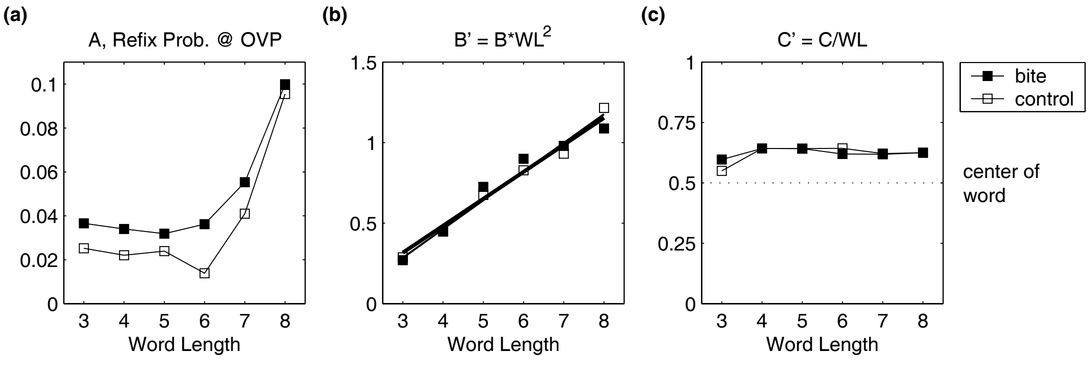

Fig. 3.10 Quadratic fit to refixation probability curves, comparison of reading with a bite bar data (full squares) vs. chin rest reading control data (open squares): Parameters *A* (panel a), *B’* (panel b), and *C’* (panel c) as a function of word length.

3.2.4 Results from Reading under Low Contrast Experiment (Exp. 5)

It is generally assumed that the main cause for the refixation OVP effect lies in the very strong drop-off of visual acuity even within the fovea (McConkie *et al.*, 1989). Refixations should be more likely when the eyes start from a non-central position, because here less information can be extracted during one fixation. When the visibility of the text is experimentally reduced, as in the low contrast condition, we would expect an overall increase in refixation probability which is modulated by initial landing position. Reducing the letter contrast should affect both parameters *A* and *B'* of the refixation probability curve: Minimum refixation probability should be increased and the refixation probability curve should be steeper, as reflected in a higher slope parameter (cf., McConkie *et al.*, 1989).

Surprisingly, reducing the letter contrast to 10% of the normal resolution did not affect refixation probability curves very much (Fig. 3.11). The OVP, as reflected in parameter *C'*, appears to be unaffected by the letter contrast manipulation (Fig. 3.12c). More importantly, the present data suggest that there is no greater penalty of not fixating at OVP when sentences are read with reduced letter contrast (Fig. 3.12b). Thus, the slope of the quadratic function, as reflected by the *B* parameter, is not increased. If anything, for longer words we observe a slightly increased parameter *A* (Fig. 3.12a). For descriptive statistics, consult Appendix M, Table M4.

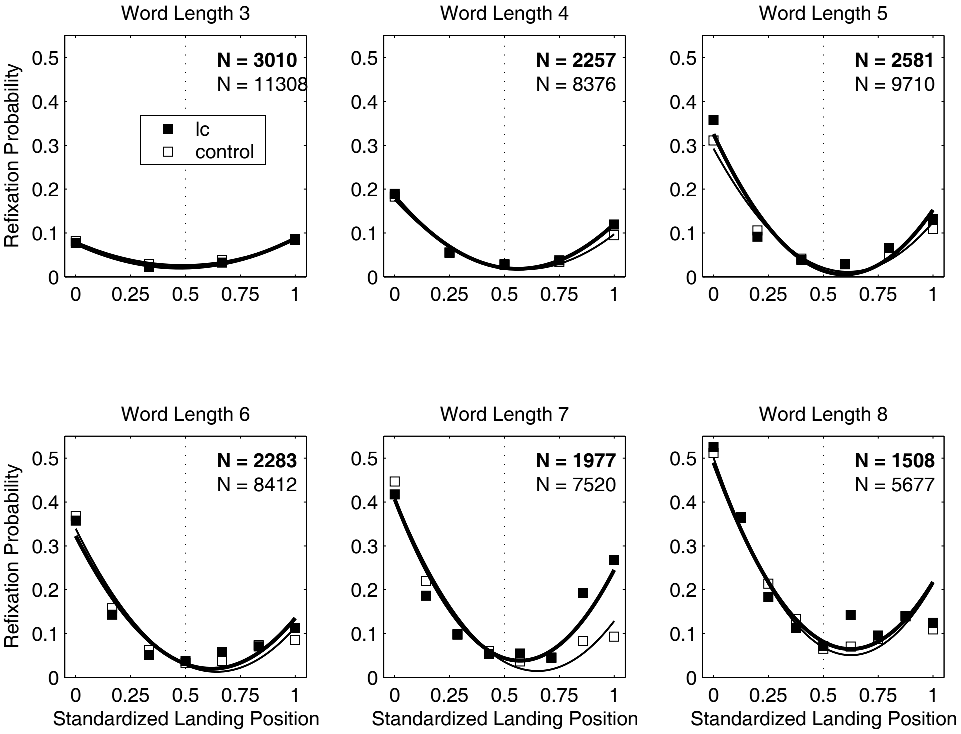

Fig. 3.11 Refixation probability curves, comparison of low contrast reading data (full squares) with normal reading control data (open squares) as a function of word length. Each panel represents data for a given word length (3 through 8). Also presented is the best fit to $y = A + B(x - C)^2$.

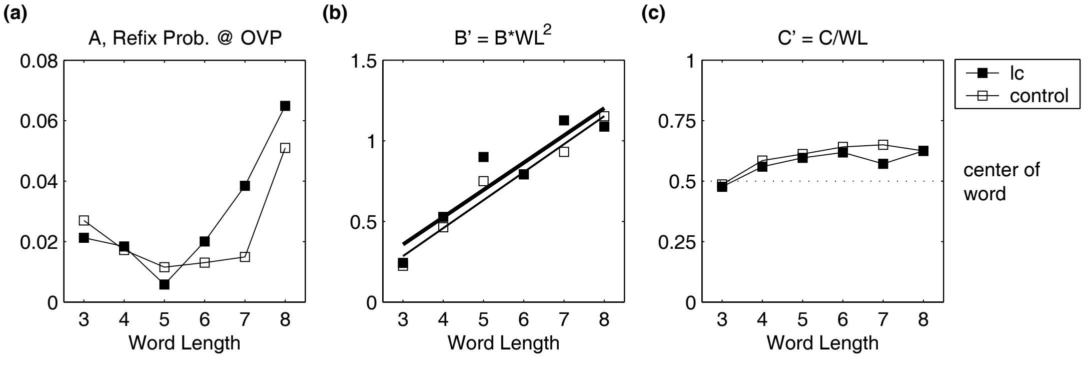

Fig. 3.12 Quadratic fit to refixation curves, comparison of low contrast reading data (full squares) with normal reading control data (open squares): Parameters *A* (panel a), *B'* (panel b), and *C'* (panel c) as a function of word length.

3.3 Summary and Discussion

In Sec. 3.1 (pp. 62), for words of differing length the *refixation OVP effect* was replicated based on data from the original reading experiment (Exp. 1, $N = 245$). When refixation probability is computed as a function of initial landing position within a word, it becomes evident that the probability of refixating a word increases as the distance of the first fixation from the center of the word increases.

Data were fitted to a quadratic function with three parameters (Eq. 1, p. 63). This procedure allows a more detailed description and interpretation of factors influencing refixation probability curves. Parameter *C'*, the horizontal offset of the curve, reflects the fixation position within a word where refixation probability is minimal; *C'* thus indicates the optimal viewing position. Parameter *A*, the vertical offset of the curve, indicates the refixation probability at OVP. Finally, parameter *B'*, the slope of the quadratic function, quantifies the penalty paid for not fixating at OVP. In the introductory analysis presented in Sec. 3.1 (pp. 62), the influence of word length on the parameters of the quadratic refixation probability curves was investigated. Parameter *C'* was close to word center, and the effect of word length on *C'* was negligible. It was therefore concluded that the center of word is the optimal viewing position. However, parameter *B'* clearly increased with word length. Also, there was a – though somewhat less systematic – word length effect on parameter *A*.

The refixation OVP effect is related to theoretical questions regarding the occurrence of refixations: (1) what circumstances give rise to different sub-populations of refixations, and (2) when are they programmed (pre-programming vs. direct control hypothesis). While the first issue will be taken up in the General Discussion (Sec. 9.3.2, pp. 234), the next Sec. 3.4 is devoted to the second question. The current focus is on the parabolic shape of the refixation probability curve. The steepness of the curve can be explained with the rapid drop in visual acuity as a function of distance from the center of the fovea (McConkie *et al.*, 1989). In that sense, the word length effect on refixation probability curves can be explained by characteristics of vision: Longer words extend further into the periphery and thus contain letters of lower perceptibility than do shorter words. This results in more refixations of longer words when the eyes are at the same distance from the center of the word. From the fact that parameter *C* was found to be close to word center, it is inferred that readers target the center of the word as the optimal viewing position. Note that in Sec. 8.3 (pp. 218) it will be investigated how the three parameters of the refixation probability curve are influenced by word identification demands, as represented by word frequency.

In Sec. 3.2 (pp. 66), the influence of experimental manipulations on the parameters of the quadratic OVP function was investigated at a descriptive level.[18] Parameters *B'* and *C'* were clearly unaffected by both the letter contrast manipulation (3.2.4), the use of a bite bar instead of a chin rest (3.2.3), as well as by reading with salient OVP (3.2.2). Thus, the OVP (as reflected in *C'*) as well the penalty of not fixating at OVP (as reflected in *B'*) were not affected by these experimental manipulations. Parameter *A*, however, is slightly increased in these experimental conditions. Given the lacking effects on *B'* and *C'*, this translates into a slight vertical upward displacement of the refixation probability curves. However, it is not clear whether this effect would reach statistical significance, if there were enough refixation data per subject available.

Interestingly, results from the *z* string "reading" experiment (Sec. 3.2.1) provided information about the nature of refixation saccades, an issue that will be taken up in the General Discussion (Sec. 9.3.2, pp. 234).

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[18] For both the experimental as well as the control condition, data were again broken down by word length.

3.4 On the Pre-Programming of (Refixation) Saccades – Results from Reading with Recurrent Sentence Shifts Experiment (Exp. 6)

The refixation OVP effect is related to the issue of refixation saccade programming. One of the reasons to design the sentence-shift experiment was to test the so-called refixation pre-programming hypothesis. Therefore, the current section is the place to discuss the analyses related to that endeavor. In the following, the rationale behind the idea of pre-planned refixation saccades will be laid out briefly.

3.4.1 The rationale underlying the refixation pre-programming hypothesis

Two causes of refixations in reading are generally agreed on: Refixations are caused by a sub-optimal landing position of the initial saccade into the word (e.g., O’Regan, 1990; O’Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984; McConkie *et al.*, 1989) and/ or lexical processing difficulty occurring during the first fixation on the word (cf., McConkie *et al.*, 1989). Both explanations are based on the assumption that the decision to refixate is made during the first fixation (direct-control hypothesis). Beauvillain and Vergilino, however, found evidence that the refixation saccade is planned *before* the execution of the initial saccade into the word. They argue for a pre-programming of refixation saccades with the initial saccade into the word (Beauvillain *et al.*, 1999; Beauvillain, Vergilino, & Dukic, 2000; Vergilino & Beauvillain, 2000; Vergilino-Perez & Beauvillain, 2004; Vergilino-Perez *et al.*, 2004).

The authors basically examine two questions: (1) whether refixation saccades are pre-planned, and (2) whether the refixation saccade amplitude depends on initial landing position. In a first study which inspired the current reading experiment the influence of initial fixation location on refixation saccades was explored (Beauvillain *et al.*, 1999; see also Beauvillain *et al.*, 2000). A double step experiment was performed in which letter strings of different lengths (7, 9, 11 letters) were shifted by one or two spaces in the same or opposite direction to that of the primary saccade. The shift was executed during the primary saccade into the item. Whereas the initial landing position distribution was clearly influenced by displacement condition, the refixation saccade amplitude distribution was not. Refixation saccade amplitude was independent of initial landing position and thus did not correct the artificially induced fixation error. This is a surprising result since one would have expected a shortening or lengthening of refixation saccade amplitude as a function of initial landing position. It was concluded that refixation saccade amplitude seems to be coded as a *constant* movement which is a function of letter string length.

In a second study (Vergilino *et al.*, 2000; see also Beauvillain *et al.*, 2000), the *length* of a target letter string was changed during the first saccade directed to it or at different times during the first fixation on it. The authors demonstrated that the amplitude of the refixation saccade triggered after *short* first fixation durations depended on the length displayed *before* the primary saccade. This result supports the hypothesis that the refixation saccade is planned before the execution of the primary saccade to the word; if the refixation saccade had been planned during the first fixation, the amplitude would have been computed from the length displayed at that time. Notably, whereas an artificial error does not involve a correction of the refixation saccade pre-program (Beauvillain *et al.*, 1999), the length change occurring during the first fixation permits a correction of the refixation program if the new information is provided sufficiently early, 150 to 200 ms before the end of the first fixation (Vergilino & Beauvillain, 2000). On the other hand, the *cancellation* of the refixation program followed by planning a saccade directed to another item requires more than 220 ms (Vergilino-Perez & Beauvillain, 2004). The authors finally approached a more reading-like situation in that they actually used words instead of meaningless letter strings: They had participants read high- and low-frequency words of 8-, 10- and 12-letters in an isolated word recognition paradigm (Vergilino-Perez *et al.*, 2004). Word frequency had an effect on refixation probability which was independent of initial landing position. The authors conclude that while most refixation saccades are preplanned, they are sometimes cancelled in case of successful lexical processing during the first fixation on a high-frequency word (cf., Sec. 8.3, pp. 218, for details and discussion).

Interestingly, the authors now further softened their claim on pre-programmed refixations in that they acknowledge that both types of refixation saccade programs – pre-planned vs. triggered during the initial fixation – might coexist (McDonald & Shillcock, 2004; McDonald & Vergilino-Perez, 2006; Vergilino-Perez *et al.*, 2004).

As for the second basic question, Beauvillain and Vergilino claim that the programming of intra- and inter-word saccades is based on differing metrics (Vergilino-Perez & Beauvillain, 2004) and/ or reference frames (Vergilino & Beauvillain, 2001). As a consequence of (pre)planning a two-fixation sequence, the initial saccade is directed toward a position near the word beginning, and the amplitude of the actual refixation saccade is believed to be coded as a constant motor vector (for details see

Sec. 7.3.3, pp. 196). When a single fixation on a word is planned, however, the saccade is thought to be directed towards the center of the word. For example, in Exp. 2 in Beauvillain *et al.* (2000) the displacement-paradigm was applied to a sequence of two 7-letter words. The first word was a high- or low-frequency noun, the second word was an adjective. During the primary saccade to the first word, the two-word sequence was displaced by one or two letters in the same or opposite direction of the primary saccade. If the secondary saccades was (pre-)planned to be a refixation, the amplitude was not modified according to the after-shift metrics. However, if the secondary saccades was directed to the second word, the landing error induced by the two-word sequence displacement during the primary saccade was corrected with the critical saccade targeting the center of the second word.

As for the pre-programming notion, it is argued that refixation saccades are pre-programmed within one package together with the initial saccades. In the existing research reports, however, it is not made very explicit whether some sort of pre-planning would also apply to inter-word saccades.

3.4.2 Predictions

Contrasting the pre-programming and the direct-control hypotheses, the following predictions can be derived. If the critical saccade was programmed during the critical fixation then this saccade should be programmed based on the after-shift coordinates[19], thus taking the experimentally induced changes in landing position into account (*direct-control hypothesis*). If necessary, the oculomotor system should respond to the unexpected landing position; these responses should manifest themselves in specific effects of shift condition (see Sec. 2.6.5.3.1, pp. 56) on, most of all, the amplitude and/ or direction of the critical saccade.

On the other hand, if the program for the critical saccade was initiated already before the execution of the preceding saccade – during which the sentence was displaced – then this saccade program was specified based on the before-shift coordinates (*pre-programming hypothesis*). Thus, not finding specific effects of shift condition on, for example, saccade length distributions would be suggestive of a pre-programming of (refixation) saccades. Note however, that adjustments (Vergilino & Beauvillain, 2000) and/or a cancellations (Vergilino-Perez & Beauvillain, 2004) of pre-planned refixation saccade programs are possible. Therefore, the existence of sentence

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[19] See Sec. 2.6.4 (p. 49) for definitions.

shift effects as such would not be entirely incompatible with the pre-programming hypothesis. For example, the refixation saccade could have been pre-planned and subsequently revised according to the after-shift landing coordinates. If so, it would be desirable to determine the temporal and spatial conditions required for such a revision and/ or cancellation.

It is reasonable to assume that both types of refixation saccades – pre-planned vs. triggered during the initial fixation – coexist (see above). The main purpose to create the current experiment was therefore to obtain evidence that a proportion of refixation saccades is indeed pre-planned. Furthermore, it is hypothesized that a pre-programming (in the sense of a parallel programming) of saccades is generally possible, for intra-word saccades (refixations) but also for inter-word saccades (cf., Sec. 9.3.4, pp. 239). Therefore, the current experiment was designed to allow a more general test of the pre-programming hypothesis. A strict test of the refixation pre-programming hypothesis would require the following experimental setup: The sentence would have to contain a target word that is relatively long to assure an increased “natural” refixation probability for that word (cf., Huestegge *et al.*, 2003). Sentence displacements would have to take place during the initial saccade into the target word. In the current experiment, however, the experimental setup was slightly different. Sentence displacements were not tied to a certain type of saccade. Also, the word material was not optimized for the critical saccade being a refixation saccade.

Generally, it should be emphasized that analyses of the present data are complicated by the dynamics of a continuous reading situation, as opposed to isolated word recognition. First, eye-movement behavior is influenced by factors like launch site distance or word frequency. Thus, single sentences reading represents a less controlled though certainly more natural situation than isolated letter string “reading”. The second problem is related to the metrics and/or coordinates considered for analyses. There are instances, in particular related to 2.5-letter shifts, where the classification of a given critical saccade as intra- or inter-word saccade does depend on whether the before-shift or after-shift metrics is considered. When contrasting the two metrics, a given saccade might change from being an inter-word saccade to an intra-word saccade, or vice versa.

3.4.3 Testing the (refixation) pre-programming hypothesis by consideration of critical saccades and/or fixations

With the following analyses, the consequences of saccade-contingent sentence displacement were investigated. First, all critical saccades following sentence displacements during forward saccades were considered (Sec. 3.4.3.1). Second, analyses were refined by an exclusive consideration of refixation cases (Sec. 3.4.3.2).

3.4.3.1 Joint consideration of inter-word and intra-word saccades

3.4.3.1.1 Proportion of saccade types

According to their direction and target, saccades can be classified as one of the following types: (1) forward inter-word saccades, (2) regressive inter-word saccades, (3) progressive refixations, and (4) regressive refixations. In a first analysis, for critical saccades in a given shift condition, relative proportions of these four saccade types were computed (Table 3.2). Computations were based on after-shift coordinates. Displacement saccades served as the control condition (see Sec. 2.6.5.3, p. 55).

Table 3.2 Reading with recurrent sentence shifts experiment. Examination of saccades following a displacement saccade. According to their direction and target, saccades were classified as one of the following types: progressive inter-word saccades, progressive intra-word saccades (refixations), regressive inter-word saccades, regressive intra-word saccades (refixations). For a given shift condition (COND), percentages of these four saccade types were computed, based on after-shift coordinates.

COND	**-2.5 LETTERS**			**-1 LETTERS**		
	INTER	**INTRA**	**Σ**	**INTER**	**INTRA**	**Σ**
PROGR	60	14	74	70	13	83
REGR	15	11	26	11	6	17
Σ	75	25	100	81	19	100
COND	**CONTROL**					
	INTER	**INTRA**	**Σ**			
PROGR	71	15	86			
REGR	9	5	14			
Σ	80	20	100			
COND	**+1 LETTERS**			**+2.5 LETTERS**		
	INTER	**INTRA**	**Σ**	**INTER**	**INTRA**	**Σ**
PROGR	74	14	88	73	18	91
REGR	9	3	12	7	2	9
Σ	83	17	100	80	20	100

For the current question, the relative proportions of progressive and regressive saccades are most informative. The relevant data from Table 3.2 are therefore visualized in Fig. 3.13. Left- and right-shifts produced more and less regressive saccades respectively than the control condition. The proportion of, lets say, regressive saccades[20] was also a function of the size of the shift: 2.5-letter shifts to the left generated more regressions than 1-letter shifts to the left, while 2.5-letter shifts to the right generated less regressions than 1-letter shifts to the right.

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[20] Note that the proportions (%) of progressive and regressive saccades add up to 100%.

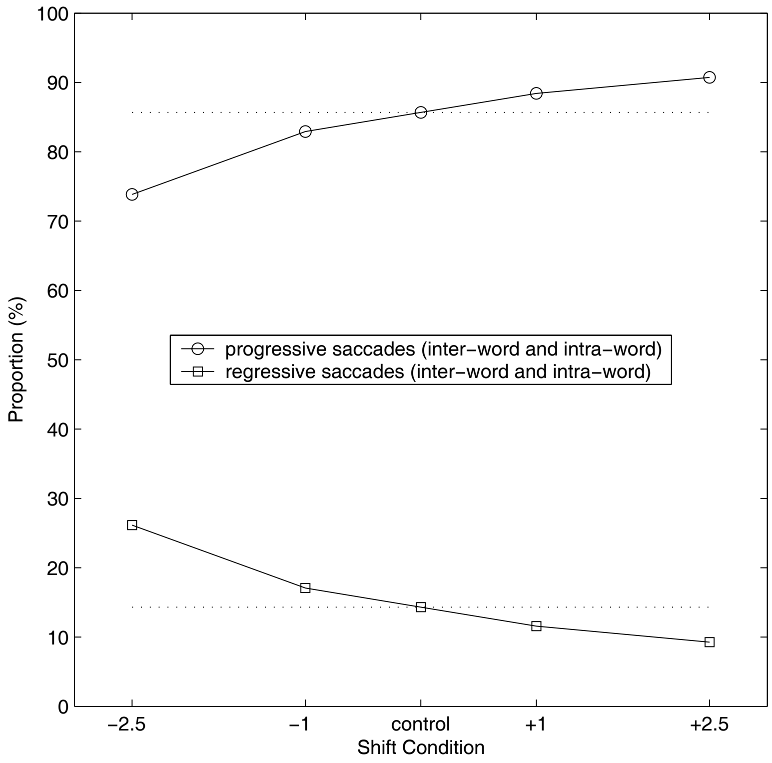

Fig. 3.13 Reading with recurrent sentence shifts experiment. Examination of saccades following a displacement saccade. According to their direction saccades were classified as either progressive (circles) or regressive (squares) saccades. Displayed is the proportion of these two (complementary) saccade types as a function of shift condition.

Thus, the oculomotor system clearly responded to the sentence displacements. Roughly, the compensation of experimentally induced overshoots is reflected in an increased proportion of regressive saccades, while experimentally induced undershoots manifest themselves in an increased proportion of progressive saccades. While this finding is not compatible with a pre-programming hypothesis put to the extreme, it is compatible with the notion of pre-programmed but labile saccade programs that are subject to modification and/or cancellation (see below).

Furthermore, the current very global analysis lends support to predictions derived for within-word landing shifts.[21] For 2.5-letter right-shift, an increased probability of progressive intra-word saccades was observed (18%, Table 3.2). On the other hand, in case of 2.5-letter left-shifts the eyes frequently corrected the severe overshoot with regressive intra-word saccades (11%, Table 3.2).

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[21] Note that the analysis was not restricted to sentence displacements during initial saccades leading to within-word landing shifts. However, in terms of the frequency of occurrence, between-word landing shifts play a minor role (see Sec. 2.6.5.1, p. 50; Table 2.1).

3.4.3.1.2 Saccade lengths distributions as a function of shift condition

The findings regarding relative proportions of different saccade types were further substantiated by considering saccade length distributions. These distributions do not allow to distinguish between inter-word and intra-word saccades. However, with the current analyses the pre-planning notion was intended to be tested for the whole range of saccades, thus both for inter-word as well as intra-word saccades. In addition, consideration of saccade length distributions circumvents the metrics issue (see Sec. 3.4.2, p. 80, last paragr.): Length and direction of the saccade following the shift-saccade do not depend on which metrics (after- vs. before-shift metrics) is considered.

Analyses revealed that shift condition systematically affected saccade length distributions for saccades following a sentence shift (Fig. 3.14a). The current analyses further substantiate the previous analyses in showing that left- and right-shifts produced more and less regressive saccades respectively than the control condition. Furthermore, for progressive saccades the length distribution is slightly shifted to the left for 2.5-letter right-shifts. Apparently, this reflects the finding of an increased proportion of progressive intra-word saccades (forward refixations) after 2.5-letter right-shifts.[22]

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[22] Note that refixation saccades are on average shorter (in terms of their length) than inter-word saccades.

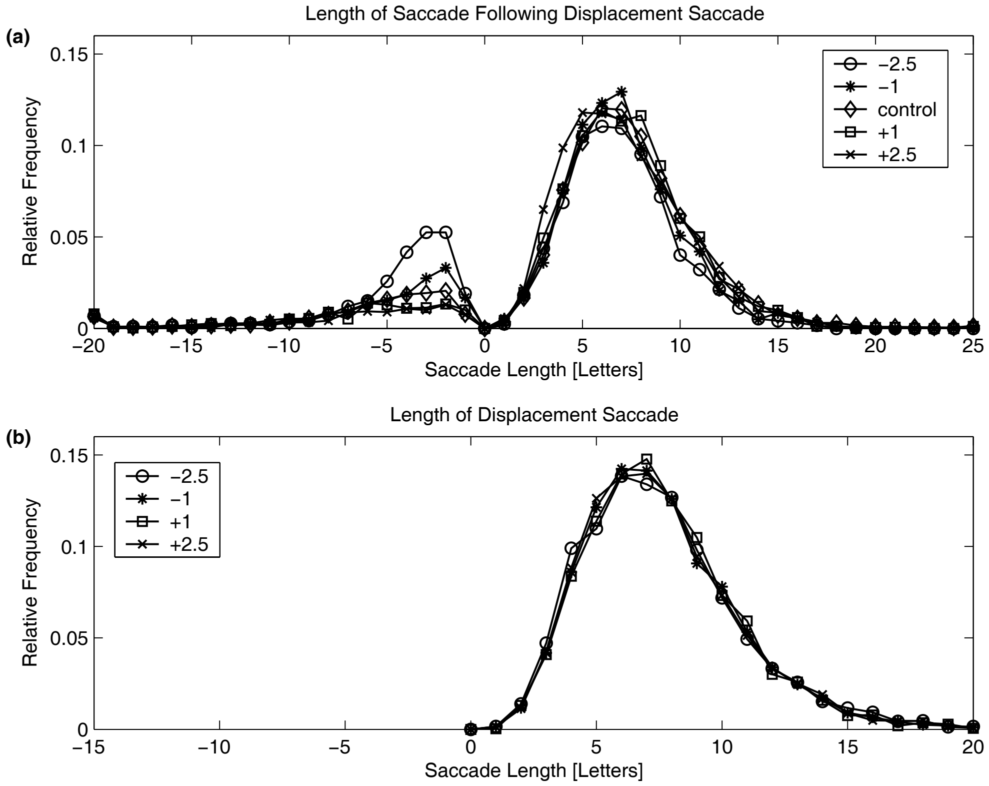

Fig. 3.14 Reading with recurrent sentence shifts experiment. (a) Distributions of saccade lengths for saccades following a displacement saccade as a function of shift condition. Negative length values represent regressive saccades. (b) Length distributions of the actual displacement saccades as a function of shift condition.

As a control analysis, length distributions of the actual displacement saccades were computed (Fig. 3.14b). Recall that shift condition was assigned randomly to a shift saccade. Therefore, no effect of shift condition on saccade length distributions is predicted, and this is what was found.

3.4.3.1.3 Saccade lengths distributions as a function of shift condition and prior fixation duration

So far, the current findings are compatible with either critical saccades being triggered and computed as a function of the (actual) landing position in after-shift coordinates (as predicted by the direct-control hypothesis) or with the pre-programming and subsequent revision of the saccade program belonging to the critical saccade.

To further contrast the two hypotheses it was investigated whether and how the duration of the critical fixation modulates the effect of shift condition on the length of the critical saccade. According to the direct-control hypothesis, the saccade program for the critical saccade is always initiated after the beginning of the critical fixation. The visuomotor system should therefore be able to integrate the experimentally changed landing position situation. If all saccades are directly controlled, the effects of shift condition on saccade length distributions should thus not be modulated by the duration of the critical fixation.[23]

According to the pre-programming hypothesis, the effect of shift condition on saccade length distributions should emerge after long critical fixations only. For example, in a letter-string length-shift paradigm it was shown that a modification of the refixation saccade amplitude was possible if first fixation duration was longer than 140 ms (Vergilino & Beauvillain, 2000). In this case, refixation amplitude was adjusted to the *final* length which was only visible during, but not before, the first fixation on a letter string.[24] According to this logic, short critical fixations reflect pre-programmed saccades that were not modified during the critical fixation. For longer critical fixations, the predictions are more complex. First, they can indicate pre-planned saccade programs that were revised during the critical fixation. Second, they can reflect pre-planned saccade programs that were cancelled and substituted by a new saccade program. Note that cancellation apparently requires more time than revision (see Sec. 3.4.1, p. 78). Third, acknowledging that both pre-planned and directly controlled saccades might coexist, long critical fixations can just as well represent cases where a saccade was programmed during the critical fixation, with no labile saccade program existing at the beginning of the critical fixation. With regard to the temporal aspect underlying this classification, it is also referred to Sec. 9.3.4 (pp. 239) where latencies of refixation saccades are investigated with SWIFT simulations.

In the current analysis, fixation duration is post hoc introduced as an independent variable. In order to contrast short and long fixation durations, a cut-off value needs to be determined. At best, the selection of such a criterion is functional in that it reflects different sub-populations of saccades and/or fixations. In the work by Beauvillain and colleagues, the selection of a cut-off value was based on the fact that

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[23] This requires that the influence of all other variables known to influence fixation duration is not modulated by displacement condition.

[24] There are, however, some inconsistencies in the data presented in research reports by Beauvillain and Vergilino. In Vergilino and Beauvillain (2000), *short* first fixation durations are interpreted as evidence for pre-programmed refixation saccades, while according to Vergilino-Perez *et al.* (2004), the refixation pre-planning hypothesis is true for *long* first fixation durations (> 200ms = refixation saccades triggered after 200 ms of the initial fixation, 75% of refixation cases in their data).

first fixation duration distributions were usually bimodal.[25] For the present data, however, duration distributions for critical fixations were not bimodal, neither when all critical fixations were considered (Fig. 3.16, p. 91) nor when the critical fixation was a first fixation followed by a refixation (Fig. 3.18, p. 95). Interestingly, for continuous reading data Vitu *et al.* (2003) reported an inflated overall regression likelihood after left-shifts, but only for fixation durations equal to or longer than 150-175 ms. Therefore, for the following analyses saccade length distributions were computed separately for short (≤ 175 ms) vs. long (> 175 ms) fixation durations (Fig. 3.15). A cut-off value of 175 ms also ensured that there was a similar number of data points available for both fixation duration conditions.

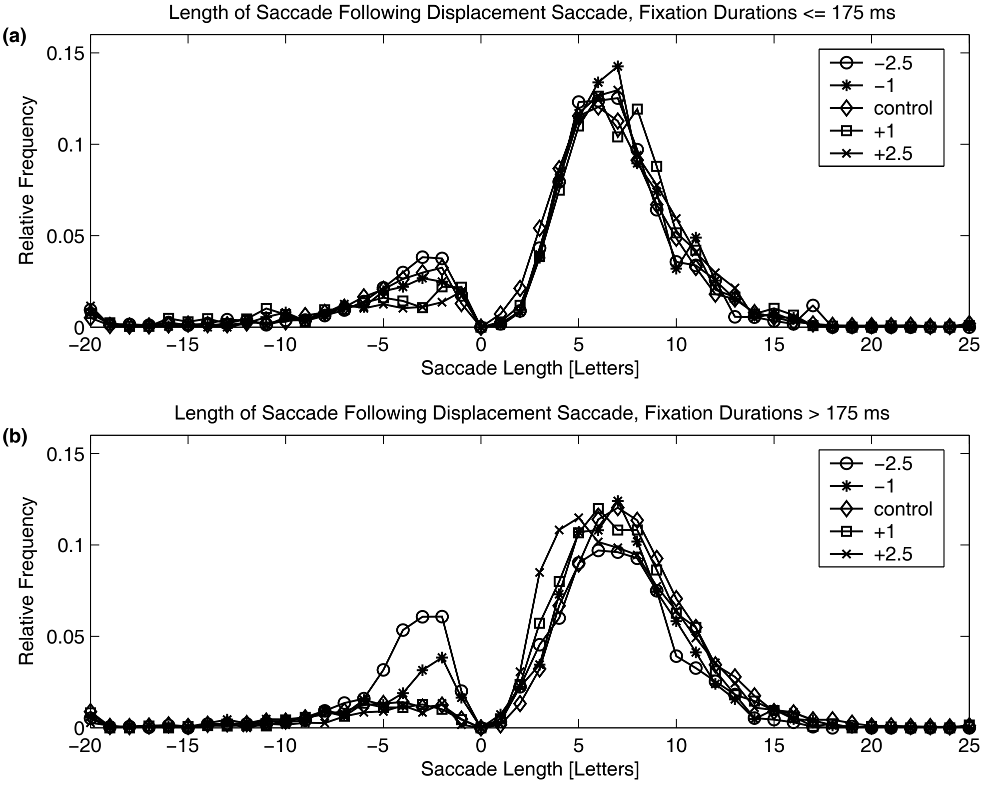

Fig. 3.15 Reading with recurrent sentence shifts experiment. Distributions of saccade lengths for saccades following a displacement saccade as a function of shift condition. Fixation durations after sentence displacement saccades <=175 ms (a) vs. > 175 ms (b). Negative length values represent regressive saccades.

As for results, the two main effects (Fig. 3.14a, Table 3.2) are stronger after long critical fixations (> 175 ms). First, for 2.5-letter right-shifts there is now a much clearer and stronger effect on progressive saccades: There is an increased proportion of short

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[25] Interestingly, in the study referred to above only three out of six subjects exhibited bimodal distributions (Vergilino & Beauvillain, 2000).

progressive saccades, most of them reflecting forward refixations. Second, there is a largely increased probability of regressive saccades after left-shifts, especially after 2.5-letter left-shifts.

For critical saccades following short critical fixations (≤ 175 ms), the picture is less clear. Apparently, there is no strong and systematic effect on progressive saccades. As for regressive saccades, however, curves for left- vs. right-shifts differ from each other. In principle, the revision of a pre-planned saccade program could also include a change of the direction of the saccade (progressive => regressive) which should, however, be associated with *longer* fixation durations. Indeed, mean fixation duration before critical regressive saccades was increased, compared to progressive saccades (Table 3.3). This prolonged fixation duration could, however, also reflect the cancellation of the current (progressive) program followed by the initiation of a new, directly controlled, regressive program. The latter scenario would suggest that regressive saccades are more under direct control than progressive saccades. Further research is certainly required on that issue. Taken together, it is not very likely that the differences for regressive saccades following short critical fixations (≤ 175 ms) are associated with pre-planned saccades. Rather, they might reflect quick ad hoc triggered corrective movements of short amplitude (cf., Vergilino-Perez *et al.*, 2004).

As a side note, for regressive saccades, comparisons of shift conditions to control data yielded somewhat puzzling results. On the one hand, after short fixation durations, data for left-shift data are similar to control data while there are less regressive saccades after right-shifts as compared to control data. On the other hand, after long fixation durations data for right-shifts behave like control data. Note, however, that the control data selected for the current analyses are sub-optimal (see Sec. 2.6.5.3, p. 55). Furthermore, a possible pre-programming would also apply to control saccades, resulting in changes of saccade properties as a function of fixation duration.

To summarize, results from the current analysis suggest that it is difficult to obtain direct empirical evidence for the existence of pre-planned vs. directly controlled saccades. As a cautious conclusion, it is argued that the data are neither compatible with the hypothesis that all saccades are directly controlled, nor with the hypothesis that all saccades are pre-programmed. Rather, they are consistent with the coexistence of both types of saccades. In particular, a proportion of saccades is pre-planned while these programs are subject to revision and/ or cancellation.

3.4.3.1.4 Fixation duration distributions as a function of shift condition

Finally, fixation durations after sentence displacements were explored. Analyses revealed that fixation durations before regressive critical saccades were on average longer than fixations durations preceding progressive critical saccades (Table 3.3). Recall that for critical fixations there was no control group available (see Sec. 2.6.5.3, p. 55). Still, normal reading control data (Exp. 1, 107 university students) suggest that fixations before regressive saccades are shorter than fixation durations before progressive saccades (193 ms vs. 201 ms). In that sense, results from the current experiment are inconsistent with normal reading data.

Table 3.3 Reading with recurrent sentence shifts experiment. Mean durations for critical fixations as a function of shift condition.

SHIFT CONDITION	**-2.5 LETTERS**	**-1 LETTER**	**+1 LETTER**	**+2.5 LETTERS**
MEAN FIXATION DURATION BEFORE PROGRESSIONS (MS)	201	199	195	190
MEAN FIXATION DURATION BEFORE REGRESSIONS (MS)	211	207	188	184
MEAN FIXATION DURATION	204	200	194	190

Because there were more regressive responses to left-shifts, we consequently observe an effect of shift condition on distributions of fixation durations after sentence displacements with fixation durations after left-shifts being longer than fixation durations after right-shifts (Fig. 3.16).

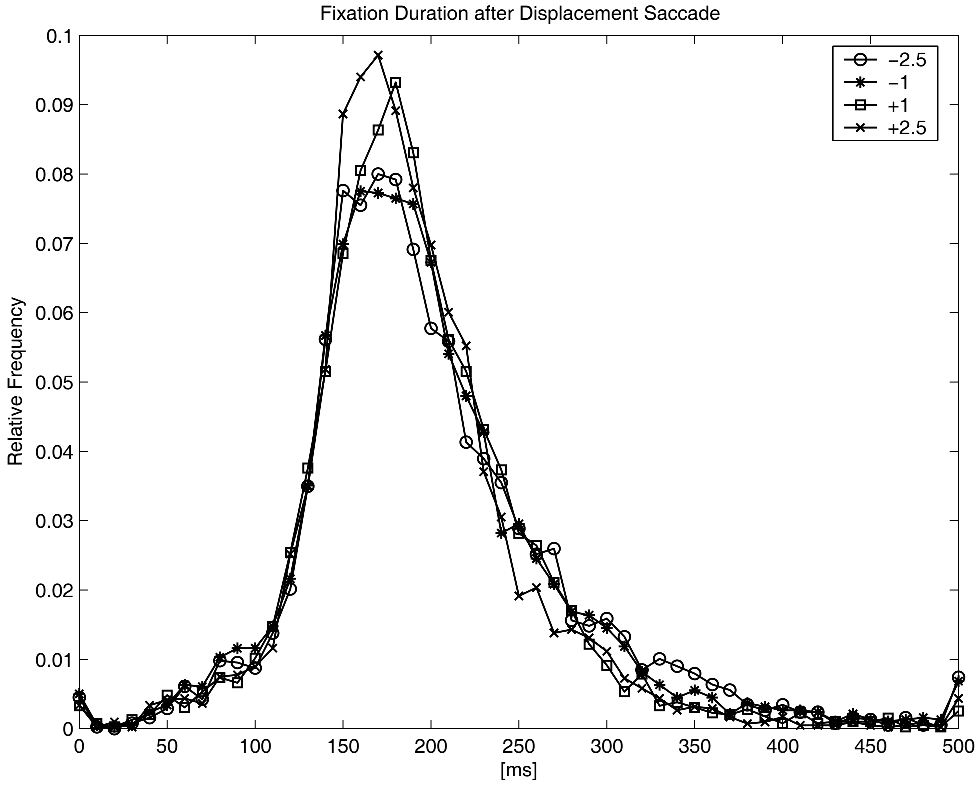

Fig. 3.16 Reading with recurrent sentence shifts experiment. Effect of shift condition on fixation duration distributions for fixations following a displacement saccade.

The fixation duration distributions are also informative with regard to the *saccadic inhibition* phenomenon (e.g., Reingold & Stampe, 2000). In the current experiment, sentence displacements always occurred during a saccade where visual perception is strongly reduced. The likelihood that the sentence shifts could have been perceived was therefore very low. However, gaze-contingent visual display changes may still produce a visual flicker that remains visible at the beginning of the following fixation (Reingold & Stampe, 2004). If this were to be the case, this should show in a dip in the fixation duration distribution, the dip being exhibited after a somewhat constant delay following the shift. This seems, however, not to be the case (Fig. 3.16). Thus, there is no evidence that the saccade-contingent sentence displacements produced visual artifacts.

3.4.3.2 Intra-word saccades: Refixation saccade amplitude distributions as a function of word length and shift condition

Next, analyses that exclusively considered refixation cases were employed. Recall that with the current experiment, the letter-string displacement-paradigm (Beauvillain *et al.*, 1999, Exp. 1; Beauvillain *et al.*, 2000, Exp. 1) was transferred to a continuous reading situation. The authors employed a double-step paradigm with long meaningless letter strings. With their research program they tackle two questions regarding (1) the pre-programming of refixation saccades, and (2) the metrics of refixation saccades as opposed to inter-word saccades (see Sec. 3.4.1, p. 78).

As for the first question, previous analyses of the present data already showed that there was a systematic effect of shift condition on saccade length distributions. Thus, critical saccades (both inter-word or intra-word saccades) frequently responded to sentence displacements. It was argued that these effects are not incompatible with the pre-programming hypothesis. Basically, the current analyses aimed at refining the previous analyses on saccade length distributions in that considerations were restricted to refixation cases only.

The second question investigated by Beauvillain and Vergilino covers the issue whether refixation saccades, as inter-word saccades, are coded in retinotopic coordinates. In experiments using the displacement paradigm, the central analysis considered distributions of refixation amplitudes[26]. For progressive refixation saccades, these distributions were found to overlap for the different displacement conditions (Beauvillain *et al.*, 1999, Fig. 1b; Beauvillain *et al.*, 2000, Fig. 1, right panels), suggesting that refixation amplitudes were not adjusted according to the after-shift metrics. It was concluded that, in case of a refixation, the eyes are sent a specific distance, regardless of initial landing position. Consequently, it was argued that refixation amplitudes are not coded as a function of the position of the item on the retina. Rather, the refixation saccade amplitude is coded as a *constant* movement vector which is solely a function of letter string length (see also Vergilino & Beauvillain, 2001; Vergilino-Perez & Beauvillain, 2004; Vergilino-Perez *et al.*, 2004). Thus, it is argued that refixation saccades, unlike inter-word saccades, are not coded in retinotopic coordinates but in motor space coordinates.

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[26] In accordance with Beauvillain & Vergilino, for the following analyses the term “refixation amplitude” was adopted which is equivalent to the more general term “saccade length” used in previous analyses of data from the current experiment.

To test the constant motor vector assumption for refixation saccade amplitudes in a continuous reading situation, the analysis scheme by Beauvillain & Vergilino was adopted. It required to select cases where the sentence was displaced during a saccade that leads to an *initial fixation* on word *w* in both *before*-shift as well as *after*-shift coordinates. This restriction implies that between-word landing shifts, i.e. experimentally induced mislocated fixations, had to be excluded from analyses.[27] As for the critical saccade, cases were selected where it was a refixation saccade according to the after-shift metrics.

Recall that displacement conditions affected refixation probabilities, both in the current experiment (Table 3.2, p. 83) as well in the displacement paradigm employed by Beauvillain *et al.* (1999, 2000). For the current analyses, refixation amplitude distributions were computed as a function of displacement condition (Fig. 3.17). Thus, for a given word length and displacement condition, data points add up to 1. Note that because of the lack of a valid control condition, the distributions for the different displacement conditions can only be compared relative to each other.

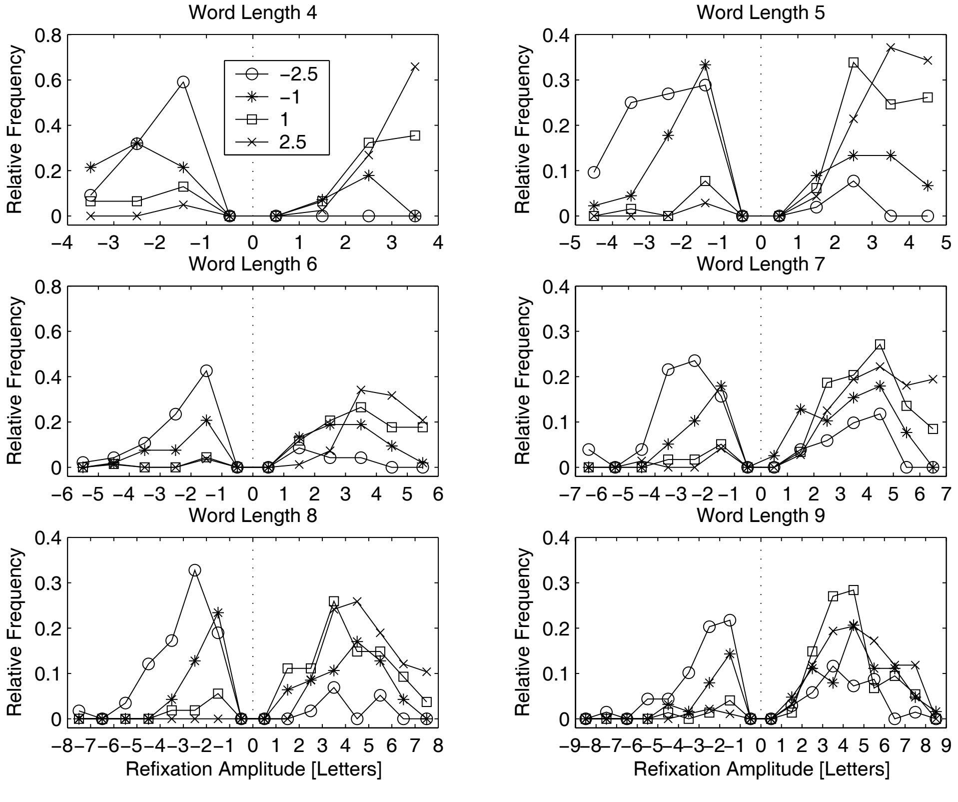

Fig. 3.17 Reading with recurrent sentence shifts experiment. Distributions of refixation saccade amplitudes as a function of word length and shift condition. Each panel represents data for a given word length (4 through 9). Negative amplitudes represent regressive intra-word saccades (backward refixations).

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[27] Also, sentence shifts during refixations or regression had to be excluded from analyses.

Within-word left-shifts, especially 2.5-letter left-shift, frequently lead to within-word overshoots. The current analyses support the prediction that these overshoots are frequently corrected with regressive refixations, a finding which was also observed by Beauvillain *et al.* (1999, 2000). In response to right-shifts, on the other hand, we observe very few regressive refixations. Note, however, that with their considerations regarding the metrics of refixation saccades, Beauvillain and colleagues exclusively focus on progressive refixations. As for progressive refixations after left-shifts, we observe a shortening of the refixation amplitude.[28] For progressive refixations after right-shifts which frequently lead to within-word undershoots, we observe a lengthening of the refixation amplitude.[29] These findings are clearly at odds with results obtained by Beauvillain *et al.* (1999, 2000), reporting that there was no effect of displacement condition on refixation amplitude. Thus, the current results are inconsistent with the constant refixation saccade amplitude reported by Beauvillain *et al.*, but they are consistent with results by Huestegge *et al.* (2003).

It would be desirable to test whether first fixation duration modulates the effect of displacement condition on refixation saccade amplitude. The effects should be less pronounced after short first fixation durations (cf., Sec 3.4.3.1.3, pp. 86). Therefore, first fixation duration distributions were computed, separately for first fixation durations after left- and/or right-shifts (Fig. 3.18).

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[28] It should be noted that it is somewhat problematic to use refixation amplitude as a dependent variable. Whether a given saccade qualifies as an inter-word or intra-word saccade in offline data analyses is also influenced by the length of a the word initially fixated as well as the initial landing position (for details on this sampling problem see Nuthmann *et al.*, in prep.).

[29] Interestingly, in a length change paradigm Vergilino *et al.* (2000) showed that shortening of the refixation saccade amplitude is more difficult than lengthening.

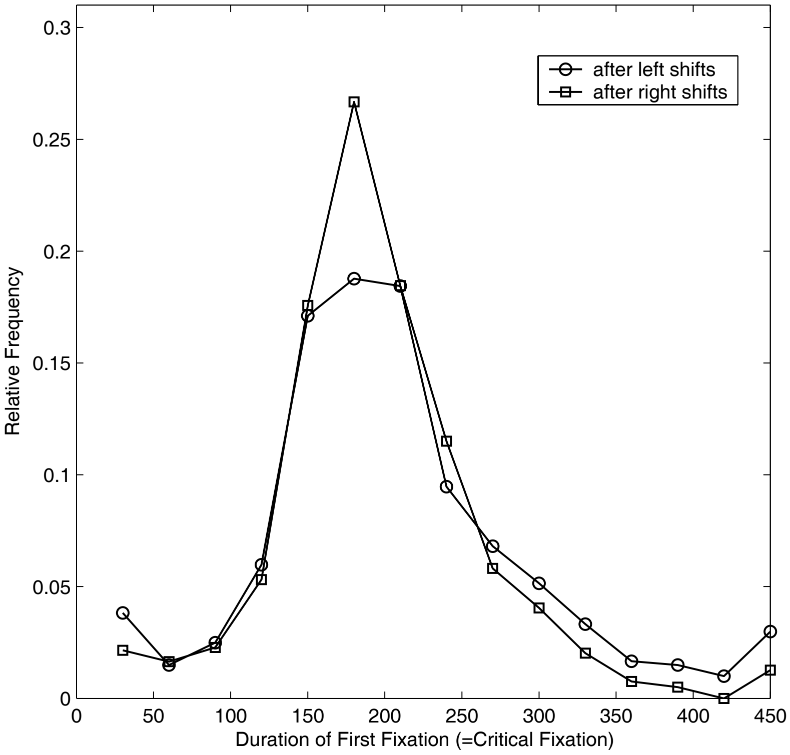

Fig. 3.18 Reading with recurrent sentence shifts experiment. Distributions of first fixation durations (= critical fixations in refixation cases) after left shifts (circles) and/or right shifts (squares).

First fixation durations after left shifts were somewhat longer than first fixation durations after right shifts, basically corroborating previous global analyses (Fig. 3.16, p. 91). Again, these distributions were not bimodal, a finding which is incompatible with results consistently reported by Beauvillain and colleagues. It is important to note that refixation saccade amplitude distributions depicted in Fig. 3.17 were based on sample sizes between 190 (word length 4, shift condition -2.5) and 435 (word length 5, shift condition -1.0). Therefore, splitting the data by fixation duration resulted in rather noisy distributions which are not presented here.

Rather, analogous to analyses in numerous papers by Beauvillain and colleagues (e.g., Beauvillain *et al.*, 2000) second fixation position was plotted as a function of first fixation position (Fig. 3.19; cf., Fig. 7.16, p. 201, for corpus analyses). For this purpose, letter position was computed as continuous variable (for details see Sec. 7.3.3.3, p. 200). Linear regression functions were fitted to the data. Data in Fig. 3.19 were visualized in a similar way as proposed by Beauvillain *et al.* (2000, Fig. 3a). The authors combined data across shift conditions, but considered data for three word lengths (7, 9, and 11) separately. In the current analysis, data for word lengths 4 to 9 were pooled, the position values were hence computed relative to the center of the word. Furthermore, not only progressive but also regressive refixation saccades were considered.

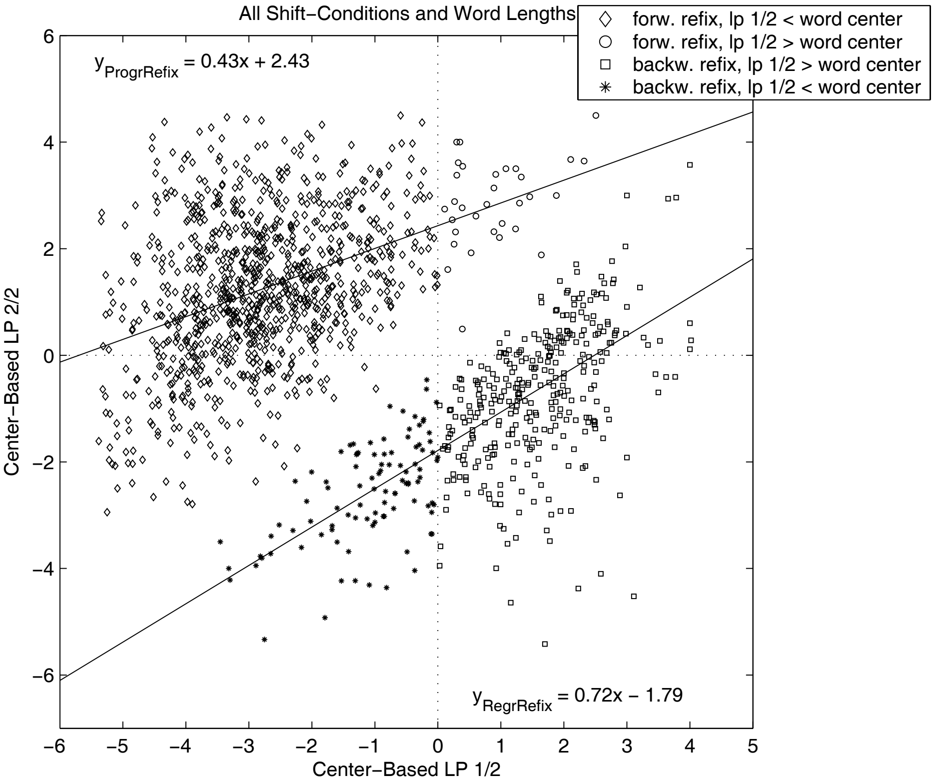

Fig. 3.19 Reading with recurrent sentence shifts experiment. Second fixation position as a function of first fixation position for progressive (diamonds and circles) and regressive (squares and stars) refixation saccades for (a) left-shift conditions, and (b) right-shift conditions. Position values were computed relative to the center of the word; data for different word lengths were pooled.

Beauvillain and colleagues consistently report a perfect linear relationship between first and second fixation position (i.e., slope = 1) which indicates that in case of a refixation the eyes are simply sent a particular distance further into the word (e.g., Beauvillain *et al.*, 2000). Thus, regardless of first fixation position the refixation saccade amplitude is applied as a constant movement vector. For the present data, however, slopes are considerably smaller than one which is interpreted as evidence against the constant motor vector assumption (Fig. 3.19). Rather, the slopes are close to 0.5. For an extensive investigation of the metrics of intra-word saccades (refixations) as opposed to inter-word saccades based on corpus data it is referred to Sec. 7.3.3.3 (pp. 200).

In a final analysis, it was tested whether the relationship between first and second fixation position is modulated by first fixation duration and/or shift condition. In a length-change paradigm, the slope of the fitted linear regression function was not modulated by first fixation duration (Vergilino & Beauvillain, 2000, Fig. 4). Even when, after long first fixation durations, the refixation saccade amplitude was recomputed taking the new string length into account, the saccade was not aimed at a precise target location within the string. For analysis of the present data, the breaking point for short vs. long first fixation durations was set to 175 ms (cf., Fig. 3.15, p. 88) which was somewhat arbitrary given the lack of bimodal first fixation duration distributions (Fig. 3.20).

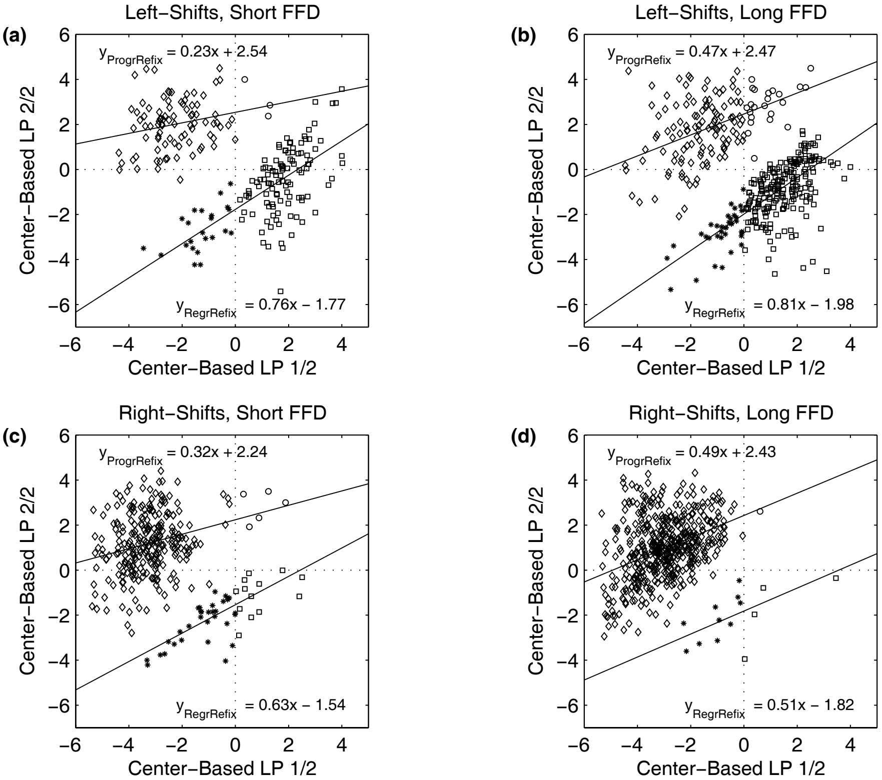

Fig. 3.20 Reading with recurrent sentence shifts experiment. Second fixation position as a function of first fixation position for progressive (diamonds and circles) and regressive (squares and stars) refixation saccades following short (≤ 175 ms) vs. long (> 175 ms) first fixations after left-shifts (panels a and b) and/ or right-shift (panels c and d). Position values were computed relative to the center of the word; data for different word lengths were pooled.

As far as the effect of shift condition is concerned, the current analysis in absolute numbers shows that after left-shifts regressive refixation saccades outnumber progressive refixations while after right-shifts progressive refixations are predominant. As for the influence of first fixation duration (first vs. long) on the slopes of the linear regression function, the effects appear not to be very systematic. Slopes considerably varied, but they were always smaller than 1. In the current more natural reading situation, launch site distance for the initial saccade into the word is variable. This is the main reason why data from the current experiment show a higher variability than data obtained by Beauvillain and colleagues (Beauvillain *et al.*, 1999; Beauvillain *et al.*, 2000). In their paradigm, letter strings were presented and displaced in isolation, and hence launch site distance was held constant.

3.4.4 Discussion of Empirical Data

Data from the reading with recurrent sentence shifts experiment showed a systematic effect of shift condition on amplitudes of critical saccades. The effect was found for both inter- and intra-word critical saccades. Importantly, it was found that the effect of shift condition on saccade length distributions was most pronounced after long critical fixations.

The mere fact that the strength of shift effects was modulated by the duration of the critical fixation was interpreted in favor of the existence of pre-planned saccades with some programs being revised and/ or cancelled during the critical fixation, others not. Schematically, the data are neither compatible with the hypothesis that all saccades are directly controlled, nor with the hypothesis that all saccades are pre-programmed. Rather, they are compatible with the coexistence of different types of saccades. More precisely, it is assumed that five types of critical saccades occurred. First, there exist pre-programmed saccades that were not modified during the critical fixation; they are associated with rather short critical fixations. Second, some pre-planned saccade programs were revised during the critical fixation, taking the changed landing position situation into account. Third, there are pre-planned saccade programs that were cancelled and substituted by a new saccade program taking the actual landing position in after-shift coordinates into account. Both revision and cancellation take time while cancellation is more time-consuming (Vergilino-Perez & Beauvillain, 2004). Fourth, there are cases where a saccade was programmed during the critical fixation, with no labile saccade program existing at the beginning of the critical fixation. Namely, shift effects are in principle compatible with both directly controlled saccades as well as pre-planned saccades that were revised and/or cancelled during the critical fixation (cf., Sec. 3.4.2, p. 80). Consequently, from the pattern of results it cannot be inferred that directly controlled saccades do not exist. Rather, it is concluded that both types of saccades, pre-planned and triggered, coexist (cf., McDonald & Shillcock, 2004; McDonald & Vergilino-Perez, 2006; Vergilino-Perez *et al.*, 2004).

Last but not least, it should be noted that a non-exclusive group of critical saccades did not correct the sentence shifts, either because it was not necessary or because there was not enough time – in terms of the duration of the critical fixation – to revise an originally pre-planned program. Furthermore, it was suspected that regressive responses, which were preceded by longer critical fixations, are more under direct control.

In existing research reports, the pre-programming notion is restricted to (progressive) refixation saccades. In contrast, with the present work it is argued that the notion of pre-planned saccades applies to both intra- as well as inter-word saccades (cf., Sec. 9.3.4, pp. 239, for an extensive discussion from the perspective of computational modeling).

Finally, the present data did not support the notion of refixation saccade amplitude being programmed as a constant motor vector. Aspects of the metrics of intra-word saccades (refixations) as opposed to inter-word saccades are extensively investigated in Sec. 7.3.3 (pp. 196). In particular, the issue of a target location for the refixation saccade is discussed based on parameters of the first-against-second-position function and/or the so-called landing position function (Sec. 7.3.3.4, pp. 204).

4 The Preferred Viewing Location (PVL)

In contrast to the optimal viewing position (see Chapter 3, pp. 62), the preferred viewing location reflects where readers actually do land in a word (Rayner, 1979). It is striking that these landing position distributions are so broad (Fig. 4.1), given that most reading theories assume that the eyes target the center of the word as the OVP (Radach & Kennedy, 2004). This considerable variance is due to oculomotor errors (McConkie *et al.*, 1988) that have two consequences. First, they lead to an over- or undershoot of the word center as the OVP, i.e., they produce considerably variance of within-word landing positions. Second, they can be so large that the eyes do not land on the intended target word, leading to mislocated fixations.

In the following, the PVL phenomenon is investigated separately for progressive inter-word saccades (Sec. 4.1), regressive inter-word saccades (Sec. 4.2), and refixations (Sec. 4.3).

4.1 Progressive Inter-Word Saccades

Landing position distributions reported in the literature are typically based on initial fixations only (e.g., McConkie *et al.*, 1988; Rayner *et al.*, 1996; Vitu *et al.*, 2001), with initial fixations comprising both single fixations as well as the first of multiple fixations on a word. However, given the wealth of data available, the current analysis could be restricted to the ideal instances where word identification required only a single fixation on a word. To obtain estimates for the mean μ_L and standard deviation σ_L for the landing position distribution of words of length L, a grid search method (in steps of 0.01) with a minimum-χ^2 criterion was applied. Best-fitting lines for word lengths from 3 to 8 are shown in Fig. 4.1; fit parameters are listed in Table 4.1.

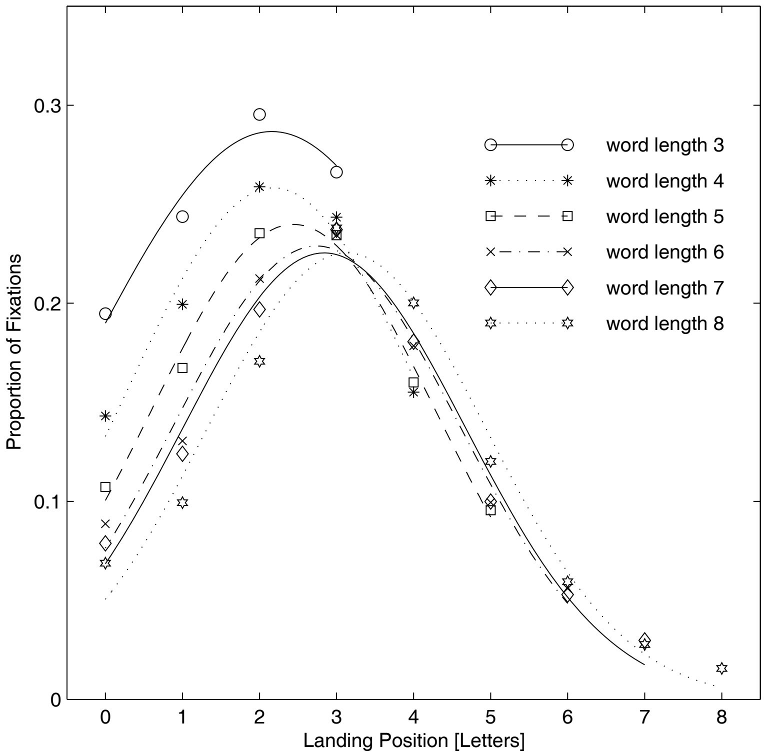

Fig. 4.1 Landing position distributions for forward saccades leading to single fixations on 3- to 8-letter words. Letter 0 corresponds to the space to the left of the word. Also presented is the best-fitting normal curve for each distribution.

Table 4.1 Means (*M*, M_C, *M'*), and standard deviations (*SD*) of landing position distributions for different word lengths, fitted to the normal curve; computations are based on single fixations.

WORD LENGTH	CENTER OF WORD	MEAN *M* [LETTER POSITION]	M_C	*M'*	*SD*	χ^2	*N*
3	2	2.16	0.16	0.72	2.38	0.00024	22682
4	2.5	2.18	-0.32	0.55	1.89	0.00041	16491
5	3	2.44	-0.56	0.49	1.85	0.00025	18798
6	3.5	2.74	-0.76	0.46	1.85	0.00063	16822
7	4	2.84	-1.16	0.41	1.84	0.00081	14604
8	4.5	3.13	-1.37	0.39	1.81	0.00119	10246

Note. $M_C = M$ – Center of word. $M' = M/$ word length. χ^2 denotes sum of squared residuals.

In comparison with the optimal viewing position (Fig. 3.1, p. 63), the preferred viewing location for 5- to 8-letter words was slightly shifted to the left (O'Regan &

Lévy-Schoen, 1987). For short words (word length 3 and 4), however, the PVL was to the right of OVP.

For each participant and every word length tested, an empirical PVL curve was computed and then fitted to a normal curve.[30] Mean and standard deviation of the fitted normal curve characterize the PVL curve. The two parameters were used as dependent variables in two separate ANOVAs with word length as within-subject factor. Mean landing position was standardized for word length: $M' = M/L$, where L denotes word length (cf., Sec. 3.1, pp. 62). There was a significant word length effect on M' [$F(5,221) = 86.12$, $MSE = 0.051$, $p = .000$, $\eta^2 = .277$]; with increasing word length a left-ward shift of the mean of the fitted normal distributions was observed. While the standard deviation was considerably increased for 3-letter words, it did not vary much for 4- to 8-letter words. Still, the word length effect on SD was statistically reliable [$F(5,221) = 16.80$, $MSE = 0.567$, $p = .000$, $\eta^2 = .069$].

4.2 Regressive Inter-Word Saccades

In languages like English and German, most reading saccades are made from left to right. However, readers do not relentlessly go forward: About 10-15% of the saccades are inter-word regressions (Rayner, 1998). As for the present data, in the original reading experiment (Exp. 1, $N = 245$) 10% of all saccades were inter-word regressions.

A number of different hypotheses have been suggested to account for the occurrence of regressive saccades in reading. They can be grouped into three basic and non-exclusive explanations (Vitu, 2005). First, according to the *comprehension hypothesis*, regressions are made in response to high-level processing demands related to sentence and text comprehension (e.g., Just & Carpenter, 1980). Second, according to *visuomotor hypotheses*, regressions are primarily determined by low-level visuomotor processes with ongoing word identification processes intervening only as a modulator of a default eye movement pattern. Third, the *word identification hypothesis* relates regressions to incomplete lexical processing of previously encountered words (e.g., Engbert *et al.*, 2005). According to corpus-based analyses, in text reading visuomotor and lexically-based regressions seem to be predominant (Vitu, McConkie, & Zola, 1998; Vitu & McConkie, 2000; Vitu, 2005).

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[30] For statistical analyses, 19 out of 245 participants were excluded because they had contributed less than 100 valid sentences to the data base, cf., Sec. 2.1.5 (p. 21).

Earlier analyses of Potsdam Sentence Corpus reading data had revealed that regression probability decreases with word length (Kliegl *et al.*, 2004). Moreover, regression probability is much higher for words which were skipped in first-pass reading (Engbert *et al.*, 2005). The current analyses investigate the distribution of landing positions for inter-word regressions. For every word length tested composite landing position distributions of inter-word regressive saccades are centered over the middle of the word (Fig. 4.2, Table 4.2), replicating a finding first reported by Radach & McConkie (1998). The standard deviation clearly increases with word length while standard deviation values for 3-5 letter words are smaller than the values presented earlier in Table 4.1 for single fixations in first-pass reading.

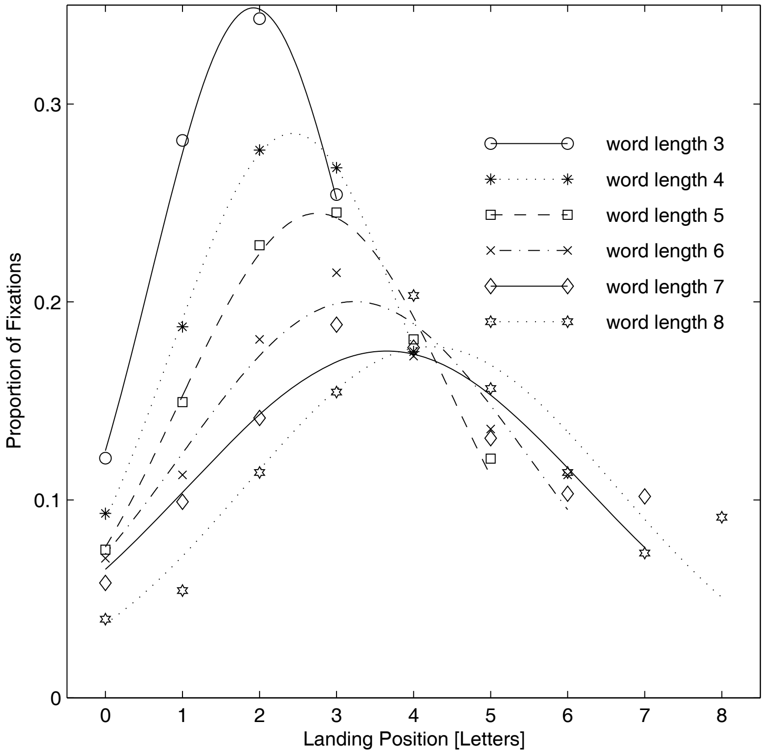

Fig. 4.2 Landing position distributions for regressive saccades targeting 3- to 8-letter words. Letter 0 corresponds to the space to the left of the word. Also presented is the best-fitting normal curve for each distribution.

Table 4.2 Regressive inter-word saccades. Means (M, M_C, M'), and standard deviations (SD) of landing position distributions for different word lengths, fitted to the normal curve.

WORD LENGTH	CENTER OF WORD	MEAN M [LETTER POSITION]	M_C	M'	SD	χ^2	N
3	2	1.92	-0.08	0.64	1.34	0.00008	7543
4	2.5	2.43	-0.07	0.61	1.6	0.00003	2801
5	3	2.75	-0.25	0.55	1.8	0.00024	3153
6	3.5	3.23	-0.27	0.54	2.27	0.00115	1900
7	4	3.65	-0.35	0.52	2.59	0.00175	1464
8	4.5	4.22	-0.28	0.53	2.39	0.00351	1107

Note. $M_C = M$ – Center of word. $M' = M/$ word length. χ^2 denotes sum of squared residuals.

Furthermore, Table 4.2 reveals that the absolute number of observed regression cases decreases with word length. Thus, short words are the most frequent target of a regression. Oftentimes, these short words have been skipped during the initial encounter (Vitu & McConkie, 2000).

Because landing positions cluster near the word center, it is concluded that inter-word regressions appear to be sent to the centers of words. Consequently, in this case "preferred" and "optimal" viewing position (see Chapter 3, pp. 62) are very similar.

4.3 Progressive and Regressive Intra-Word Saccades (Refixations)

In refixation cases, we have to distinguish between the initial saccade followed by a refixation ("1/multiple") and the actual refixation saccade (e.g., "2/2"). In Sec. 7.3.3 (pp. 196), the refixation saccade is considered. The current analyses, however, focus on the initial saccades in refixation cases. The analyses relate to the current theoretical debate regarding the programming of intra-word saccades as opposed to inter-word saccades.

In particular, McDonald & Shillcock (2004) promote the refixation pre-programming hypothesis (cf., Sec. 3.4.1, pp. 78) with results from corpus analyses. As Vergilino-Perez *et al.* (2004), they emphasize that landing position distributions differ between single-fixation and refixation cases. For single-fixation cases, they observed a mean landing position which is close to word-center for all word lengths examined. In contrast, there was only a tiny influence of word length on the initial fixation position for the refixation cases: The mean landing position was around the second letter position. They then conclude that for at least some proportion of the refixation cases, initial saccades were not aimed at the center of the target word, but at a target location near the beginning of the word. In this view, the difference in mean initial fixation position between single-fixation and refixation cases is a *consequence* of refixation *pre*planning and not a *cause* of *directly controlled* refixation planning (see also Vergilino-Perez *et al.*, 2004).

The following analyses further explore the PVL phenomenon for single-fixation cases (see Fig. 4.1, Table 4.1), now contrasted with refixation cases. Saccades that lead to a single fixation (1/1) on a word are believed to represent an optimal case of efficient word recognition. The simplest multiple-fixation sequence is the 2-fixation case with the refixation (second saccade) being either progressive or regressive. In Fig. 4.3a, for a given word length and fixation type, means and standard errors of the observed landing positions are given (cf., McDonald & Shillcock, 2004). The word length effect was captured by fitting linear regression functions to the data. As opposed to panel a), panel b) through d) depict means and standard deviations of normal curves that were fitted to the empirical data (cf., McConkie *et al.*, 1988).[31] Note that distributions for "1/multiple" were not Gaussian in shape and could thus not be fitted by a normal curve.

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[31] When discussing Fixation-Duration IOVP effects for two-fixation cases (Sec. 5.1.2, pp. 126), landing position distributions are presented for forward refixations (Fig. 5.3) and backward refixations (Fig. 5.4), for both first saccades (panel a in the respective figure) and second saccades into a word of a given length (panel b). The second saccade is the actual refixation saccade.

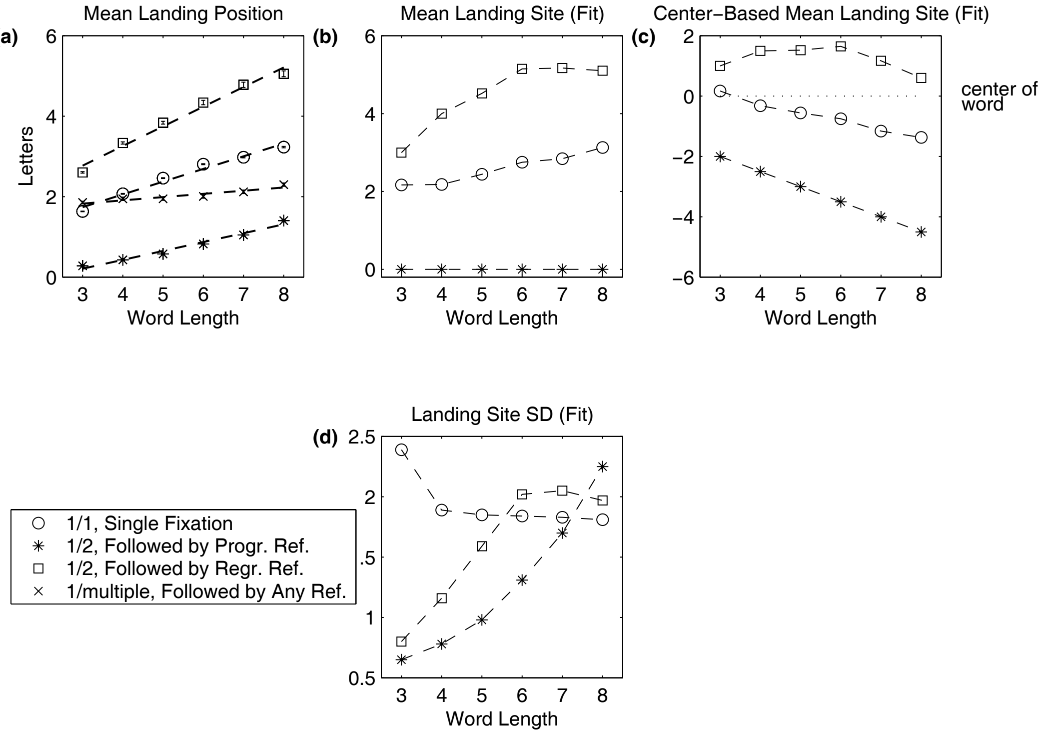

Fig. 4.3 Parameters of landing position distributions as a function of word length and fixation type. For means depicted in panel (a), mean eye position of all fixations on a word of a given length was computed. For panels (b) through (d), however, a normal curve was fitted to the empirical distribution. In this case, mean and standard deviation are parameters of a distribution fit to the empirical data.

Interestingly, for single-fixation cases the current analysis confirms that mean landing position (Fig. 4.3a) moves rightward as a linear function of word length. When center-based mean landing site is considered (Fig. 4.3c), it becomes clear that the values are close to word center with a slight leftward shift increasing with word length (see Table 4.1). When considering (indeed) *all* initial fixations that are followed by a refixation, there is only a very small, though still systematic, influence of word length on mean initial landing position which is around the second letter position ("*x*"-line in Fig. 4.3a), replicating McDonald & Shillcock (2004). However, the picture drastically changes when progressive refixations ("*"-line) and regressive refixation (line with squares) are considered separately (though restricted to 2-fixation-cases in the present analysis). In this case, the slopes of the fitted linear regression functions are *similar* for all three cases (1/1, 1/2 followed by a progressive and/or regressive refixation) while the vertical offsets differ. Thus, differences in landing positions are not necessarily a strong argument in favor of a pre-programming hypothesis. Rather, 1/2 saccades could just as well represent cases of severe within-word undershoot or overshoot, ad hoc corrected with a progressive or regressive refixation saccade (2/2).

4.4 Influence of Experimental Manipulations on Parameters of the PVL Curve

In the current section, the influence of experimental manipulations on mean and standard deviation of the preferred viewing location normal curve is investigated. For each participant and every word length tested, an empirical PVL curve was computed and then fitted to a normal curve. The fit was done based on a landing position axis that was standardized for word length (cf., Sec. 3.1, pp. 62). Mean and standard deviation of the fitted normal curve characterize the PVL curve. For proportions, means and standard deviations presented in this section, values were averaged across subjects.

To ensure stable participant-based curves showing the characteristic Gaussian shape, computations were based on *all* reading fixations except the first and last fixations in a sentence as well as fixations being shorter than 30 ms and longer than 1000 ms. Thus, different than in the previous sections, the peculiarities of different types of fixations and/or saccades were not taken into account.

4.4.1 Results from *Z* String "Reading" Experiment (Exp. 2)

Landing position distributions are very similar for z "reading" data vs. "normal" reading control data (Fig. 4.4, Fig. 4.5; descriptive statistics: Appendix N, Table N1).

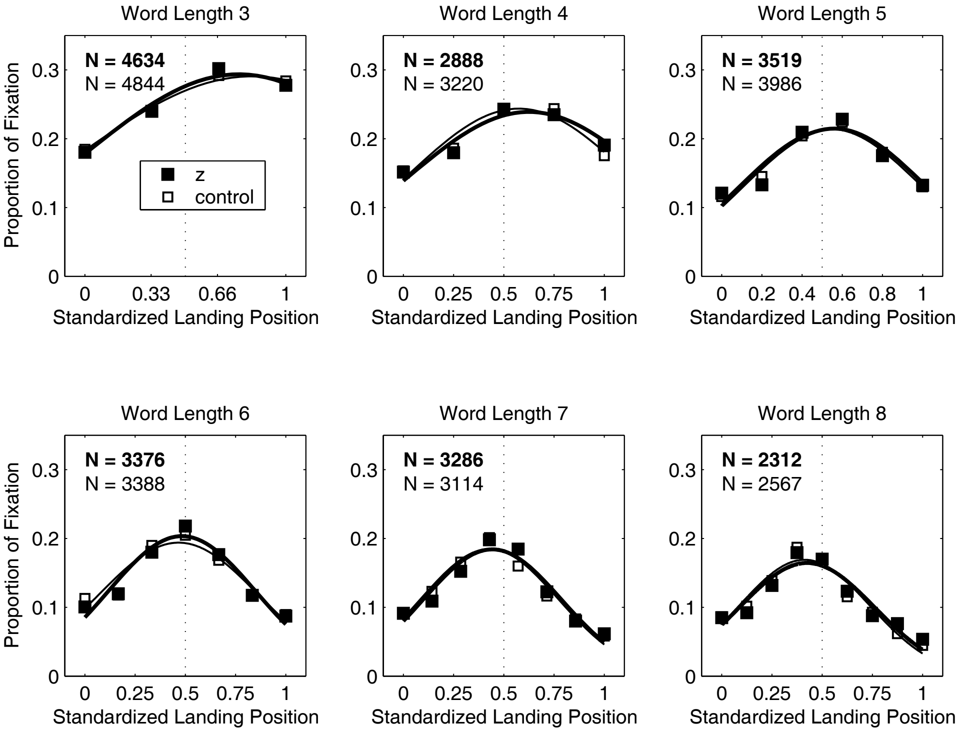

Fig. 4.4 Landing position distributions, comparison of *z* string "reading" data (full squares) with "normal" reading control data (open squares) as a function of word length. Each panel represents data for a given word length (3 through 8). Also presented is the best-fitting normal curve for each distribution.

For both *M'* and *SD*, in separate analyses, a 2 × 6 repeated measures ANOVA with "experimental condition" and "word length" as within-subject factors was conducted. Neither means [$F(1,30) = 0.006$, $p = .937$] nor standard deviations [$F(1,30) = 0.875$, $p = .357$] of the Gaussian landing position distributions did differ when *z* string "reading" was compared with normal reading. There was, however, a significant word length effect for both *M'* and *SD* (see Appendix O, Table O1).

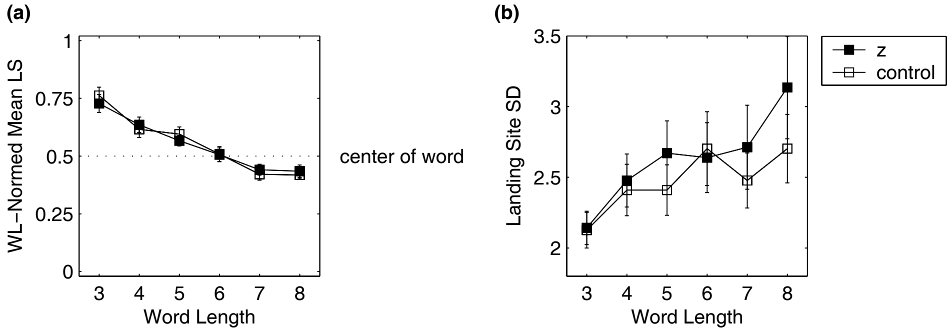

Fig. 4.5 Normal fit to landing position distributions, comparison of *z* string "reading" (full squares) with "normal" reading control data (open squares): *M'* (panel a) and *SD* (panel b) of the fitted normal curve as a function of word length.

The results are quite consistent with prior studies reporting (more or less) no reliable differences in landing positions between *z* string "reading" data and normal reading data (Rayner & Fischer, 1996; Vitu *et al.*, 1995, although applying a completely different analysis scheme). Thus, where the eyes land within a word seems not to reflect higher levels of processing.

4.4.2 Results from Reading with Salient OVP Experiment (Exp. 3)

Experiment 3 aimed at the experimental manipulation of oculomotor errors. It was investigated whether it was possible to reduce the variance of landing position distributions by marking the OVP of certain words. Analyses were based on all words (and thus not only words with salient OVP). Unfortunately, landing position distributions for "reading with salient OVP" and "normal reading" data are remarkably similar (Fig. 4.6, Fig. 4.7; descriptive statistics: Appendix N, Table N2).

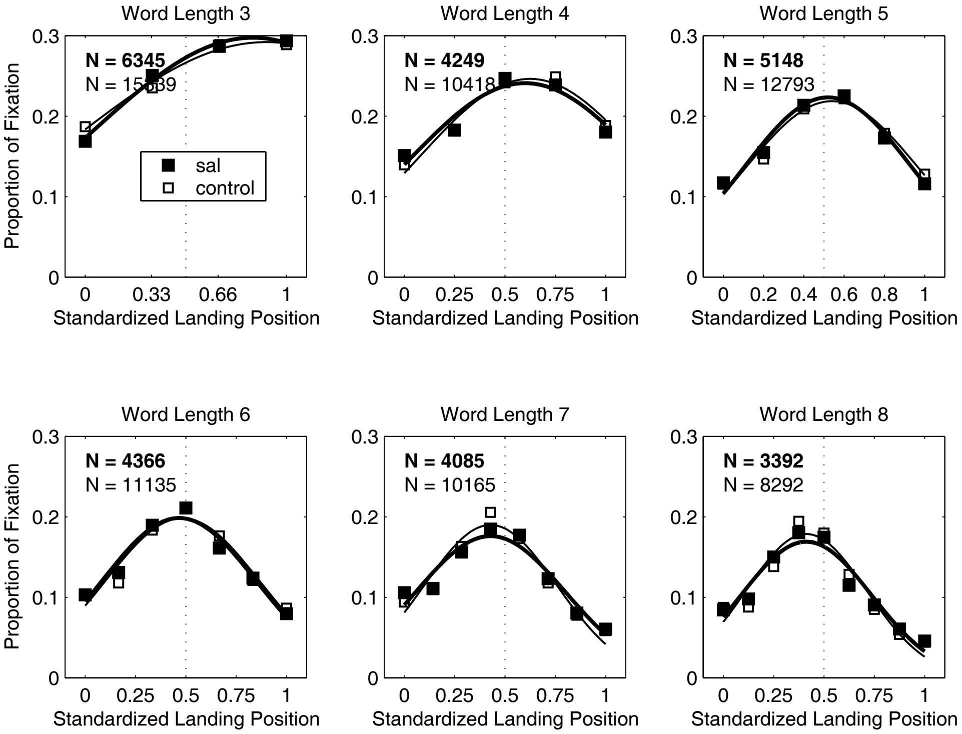

Fig. 4.6 Landing position distributions, comparison of reading with salient OVP data (full squares) with control data (open squares) as a function of word length. Each panel represents data for a given word length (3 through 8). Also presented is the best-fitting normal curve for each distribution.

In separate analyses for means and standard deviations of the normal curves that were fitted to the word-length dependent empirical landing position distributions, an ANOVA with “experimental condition” (reading with salient OVP vs. normal reading) as between-subject factor and “word length” as within-subject factor was employed. There was no main effect of the experimental manipulation on neither mean nor standard deviation of the Gaussian landing position distributions. However, word length significantly affected both parameters (for a complete report on statistical analyses see Appendix O, Table O2). In addition, for *SD* there was a significant “experimental condition” × “word length” interaction [$F(5,137) = 2.42$, $p = .045$].

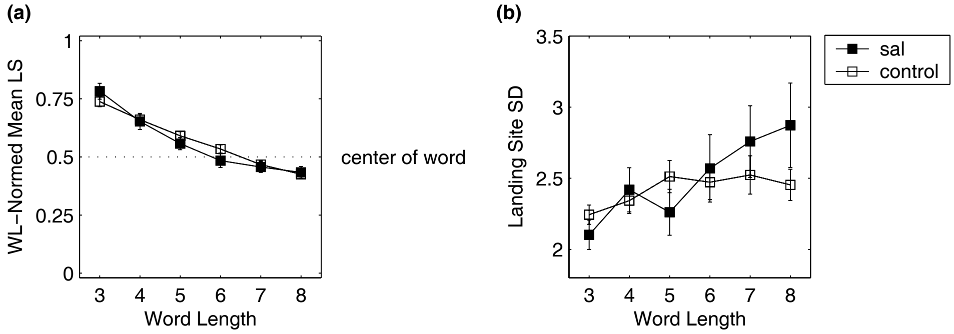

Fig. 4.7 Normal fit to landing position distributions, comparison of reading with salient OVP data (full squares) with "normal" reading control data (open squares): *M'* (panel a) and *SD* (panel b) of the fitted normal curve as a function of word length.

4.4.3 Results from Reading with a Bite Bar Experiment (Exp. 4)

Interestingly, in an experimental condition where participants' head movements were eliminated by using a bite bar, landing position distributions are shifted to the right and have a greater standard deviation (Fig. 4.8).

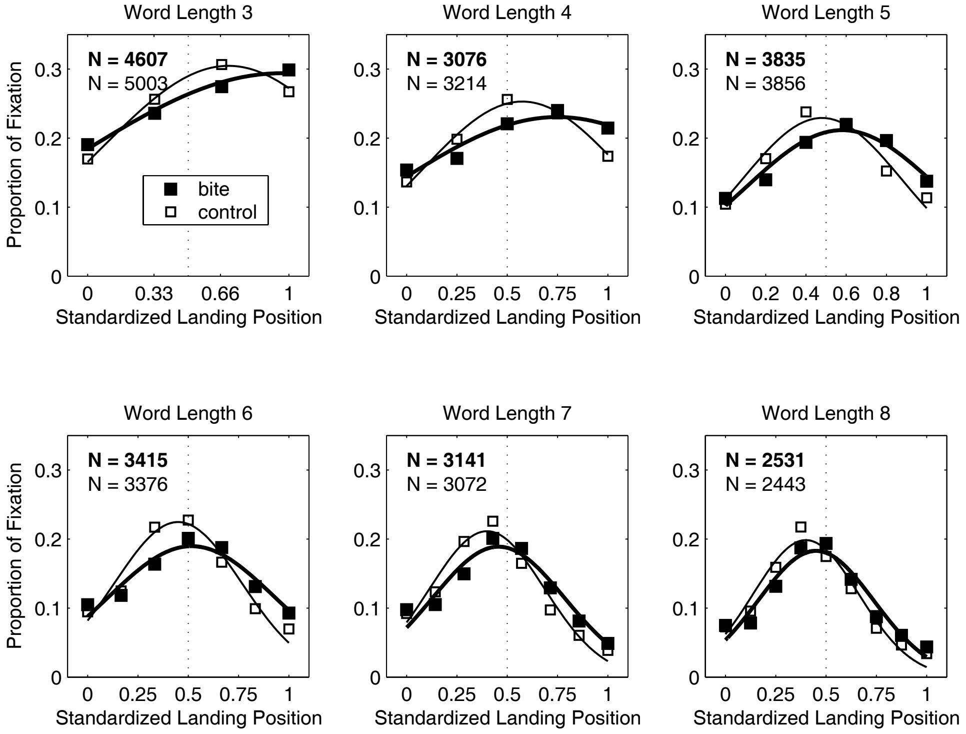

Fig. 4.8 Landing position distributions, comparison of reading with a bite bar data (full squares) vs. chin rest reading control data (open squares) as a function of word length. Each panel represents data for a given word length (3 through 8). Also presented is the best-fitting normal curve for each distribution.

Consequently, parameters *M'* and *SD* of the fitted normal curve are considerably higher in the bite bar reading condition than in the chin rest reading data (Fig. 4.9, descriptive statistics: Appendix N, Table N3). These differences are statistically significant [*M'*: *F*(1,60) = 5.01, *p* = .029; *SD*: *F*(1,60) = 6.20, *p* = .016]. In addition, there is a significant word length effect on *M'* [*F*(5,56) = 55.40, *p* = .000] but not on *SD* (for complete information on statistical analyses see Appendix O, Table O3).

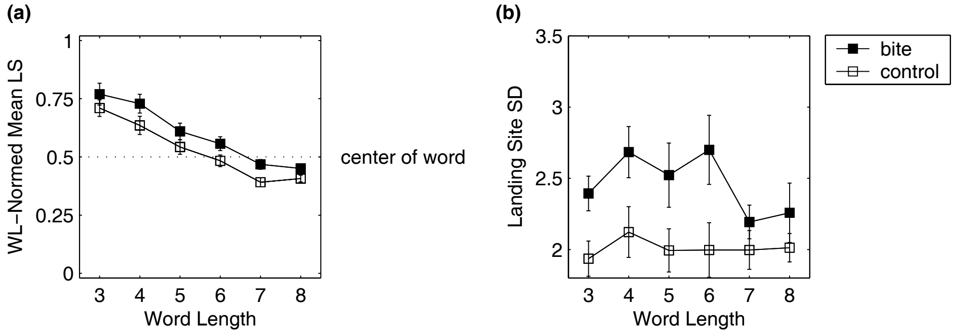

Fig. 4.9 Normal fit to landing position distributions, comparison of reading with a bite bar data (full squares) with chin rest reading control data (open squares): *M'* (panel a) and *SD* (panel b) of the fitted normal curve as a function of word length.

4.4.4 Results from Reading under Low Contrast Experiment (Exp. 5)

Interestingly, reducing the letter contrast to 10% of the normal resolution apparently did not affect landing position distributions (Fig. 4.10).

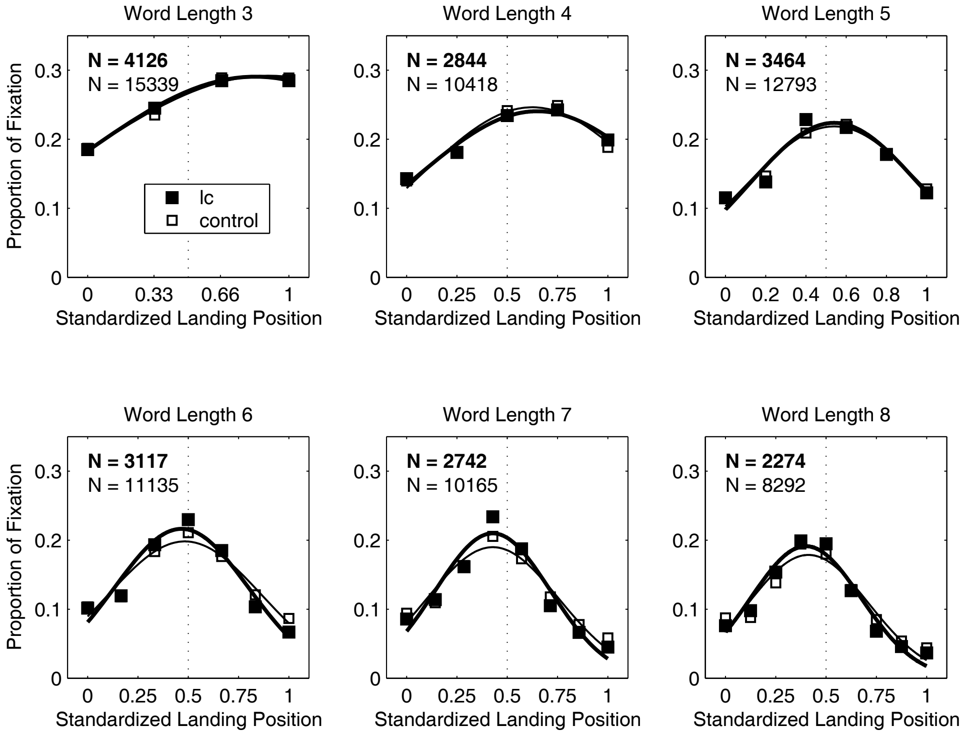

Fig. 4.10 Landing position distributions, comparison of low contrast reading data (full squares) with normal reading control data (open squares) as a function of word length. Each panel represents data for a given word length (3 through 8). Also presented is the best-fitting normal curve for each distribution.

Parameters *M'* and *SD*, characterizing the landing position distributions, did not significantly differ when reading with low letter contrast was compared with reading with normal letter contrast (Fig. 4.11; descriptive statistics: Appendix N, Table N4; information on statistical analyses: Appendix O, Table O4). However, there was a significant word length effect on *M'* [$F(5,127) = 45.07$, $p = .000$].

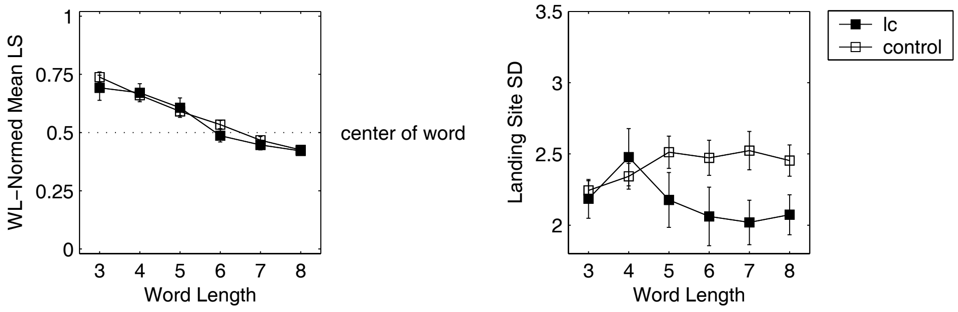

Fig. 4.11 Normal fit to landing position distributions, comparison of low contrast reading data (full squares) with normal reading control data (open squares): *M'* (panel a) and *SD* (panel b) of the fitted normal curve as a function of word length.

4.4.5 Results from Reading with Recurrent Sentence Shifts Experiment (Exp. 6)

For the reading experiment with recurrent sentences shifts, analyses on the PVL phenomenon will not follow the scheme established in the preceding sections where landing position data from the experimental manipulation were compared to normal reading control data. Rather, the effects of saccade-contingent sentence displacements (Sec. 4.4.5.1) as well as the readers' oculomotor responses to sentence displacements (Sec. 4.4.5.2) are examined.

4.4.5.1 Sentence-shift saccades

Again, only sentence shifts during *forward* saccades were considered (cf., Sec. 2.6.5.3, p. 55). Separate analyses were conducted for *within*-word vs. *between*-word landing shifts.

4.4.5.1.1 Within-word shift saccades

The following analyses consider landing positions on words fixated after sentence-shift saccades leading to within-word landing shifts. Data are plotted as a function of word length and shift condition, in either *after*-shift coordinates (Fig. 4.12) or *before*-shift coordinates (Fig. 4.13).[32] Note that the sentence shifts induced artificial changes in landing position. A sentence shift to the left (-1 or -2.5 letters) led to a rightward shift of landing position distributions and thus frequently provoked an overshoot of the center of the word. A sentence shift to the right (+1 or +2.5 letters) led to a leftward shift of landing position distributions and thus oftentimes provoked an undershoot of word center. When data are plotted in *after*-shift coordinates, the amount of landing position distribution shift nicely corresponds to the amount of sentence shift (Fig. 4.12). Distributions are based on sample sizes between 91 (word length 10, shift condition -2.5) and 506 (word length 5, shift condition +1).

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[32] See Sec. 2.6.4 (p. 49) for definitions.

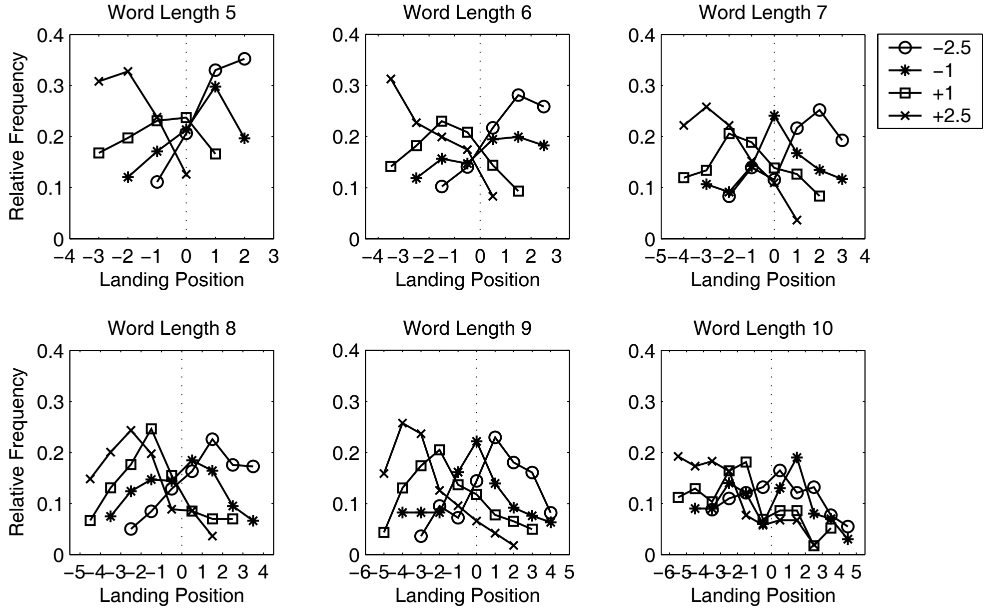

Fig. 4.12 Reading with recurrent sentence shifts experiment. Landing position distributions for sentence-shift saccades leading to *within*-word landing shifts. Computations are based on *after*-shift coordinates. Data are plotted as a function of word length and shift condition, with each panel representing data for a given word length (5 through 10).

However, when before-shift coordinates are considered (Fig. 4.13), landing position distributions are normally distributed with a mean at or slightly left of word center, reflecting the preferred viewing location phenomenon (see Sec. 4.1, pp. 100). Distributions for 5-letter words in the 2.5-letter shift conditions are not so well-behaved; this is due to the fact that 2.5-letter shifts, in either direction, mostly lead to between-word landing shifts (cf., Fig. 2.12, p. 51).

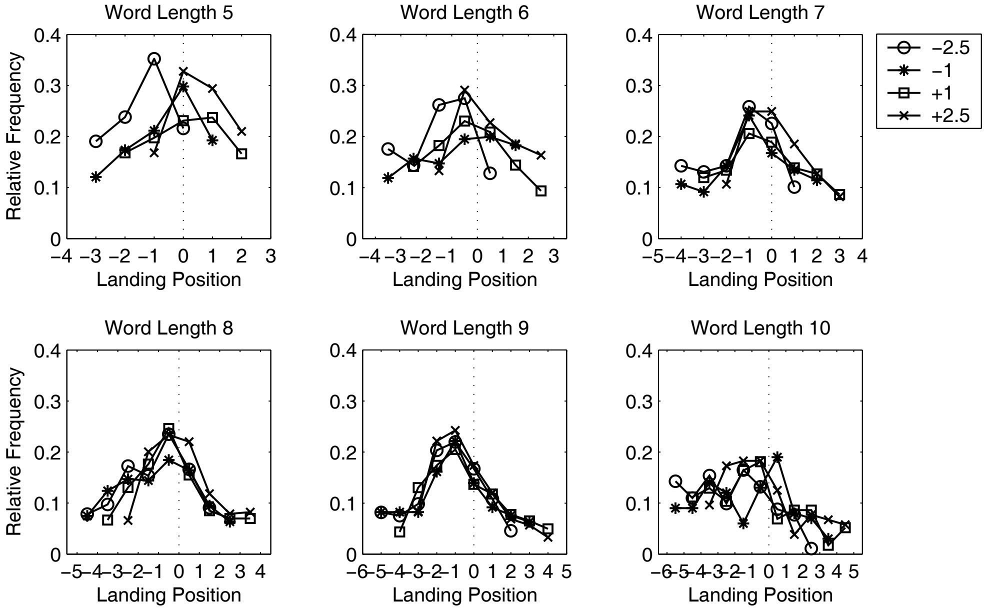

Fig. 4.13 Reading with recurrent sentence shifts experiment. Landing position distributions for sentence-shift saccades leading to *within*-word landing shifts. Computations are based on *before*-shift coordinates. Data are plotted as a function of word length and shift condition, with each panel representing data for a given word length (5 through 10).

Note that before-shift landing position distributions are *narrower* for *within*-word shifts (Fig. 4.13) compared to distributions comprising *all* shift saccades (Fig. 2.16, p. 57), the reason for this being that before-shift landing positions at either end of the word frequently lead to *between*-word shifts. In both Fig. 4.12 and Fig. 4.13, depending on which shift condition in which metrics is considered, extreme landing positions at either end of the word are lacking. For the two left-shift conditions (-1, -2.5 letters), in the before-shift metrics the right-most landing positions do not exist, whereas in the after-shift metrics the left-most landing positions do not occur: If the eyes, without the shift, would have landed at the end of a word, they do land, due to the shift, at the beginning of the following word. Likewise, for the right-shift conditions, the left-most landing positions (before-shift metrics) and/or right-most landing positions (after-shift metrics) cannot exist. Again, these position combinations are associated with *between*-word landing shifts.

4.4.5.1.2 Between-word shift saccades

The following analyses shed light on the circumstances under which *between*-word shifts occurred. Note that sentence displacements leading to between-word shifts experimentally induce mislocated fixations. Lets start with the two left-shift conditions. Generally, if the sentence is shifted to the *left*, an artificial *over*shoot is induced. If, without the shift, the eyes would have landed at the *end* of a target word (Fig. 4.14, circles connect with broken lines), the eyes now – due to the shift to the left – land at the *beginning* of the *next* word (Fig. 4.14, circles connected with straight lines). Thus, in this case the left-shift results into a *between*-word *overshoot* (unintended skipping and/or failed refixation). Conversely, if the sentence is shifted to the *right*, an artificial *under*shoot is induced. If, without the shift, the eyes would have landed at the *beginning* of a target word (Fig. 4.14, *x* connected with broken lines), the eyes now – due to the shift to the right – land at the *end* of the *preceding* word (Fig. 4.14, *x* connected with straight lines). Thus, in this case the right-shift results into a between-word undershoot (failed skipping and/or unintended refixation). For logical reasons, the 1-letter shift conditions provided one landing position data point only; these data are not presented in Fig. 4.14.

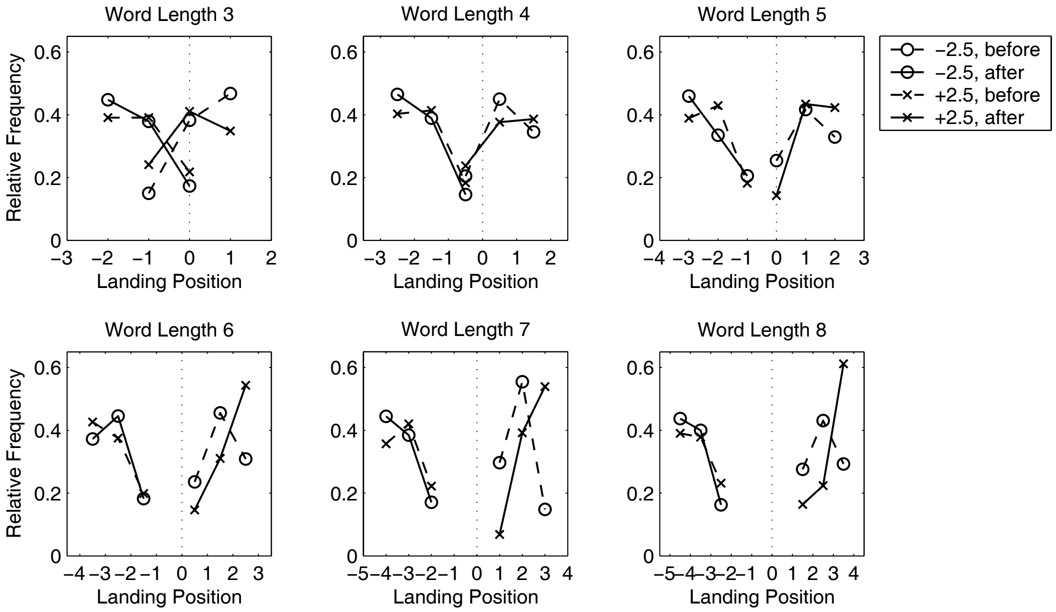

Fig. 4.14 Reading with recurrent sentence shifts experiment. Landing position distributions for 2.5-letter shifts resulting into *between*-word over- and or undershoots. Computations are based on *before*-shift coordinates (broken lines) and/or *after*-shift coordinates (broken lines). Data are plotted as a function of word length and shift condition, with each panel representing data for a given word length (3 through 8).

4.4.5.2 Critical saccades following sentence-shift saccades

The preceding analyses showed how landing position distributions for the actual displacement saccades were artificially changed due to the experimental manipulation. In a next step, the critical saccades following the displacement saccades were considered. These are the saccades that should potentially correct the sentence displacements. Recall that these critical saccades were never displacement saccades themselves. Again, all saccades following shifts during forward saccades were considered (cf., Sec. 2.6.5.3, p. 55). Inter-word and intra-word critical saccades were jointly considered.

Specific predictions about how the eyes might respond to experimentally induced landing shifts were derived from landing position distributions (Sec. 2.6.5.3.1, pp. 56). Theoretically, these predictions were tied to the more general assumption that saccade targeting is word-based, with the center of the word as the optimal landing position. Analyses presented in Sec. 3.4.3 (pp. 82) suggested that, if necessary, sentence displacements were indeed frequently accompanied by corrective oculomotor responses. The current analyses add to these data in that they investigated landing position distributions for critical saccades. Interestingly, the well-known PVL phenomenon emerged (Fig. 4.15) with no effect of shift condition on landing position distributions. Thus, the present data further support the previous findings on corrective oculomotor responses to sentence displacements. Beyond that, the current data also support the notion of saccade targeting being word-based, with the center of word as an optimal landing position (cf., Feng *et al.*, 2005).

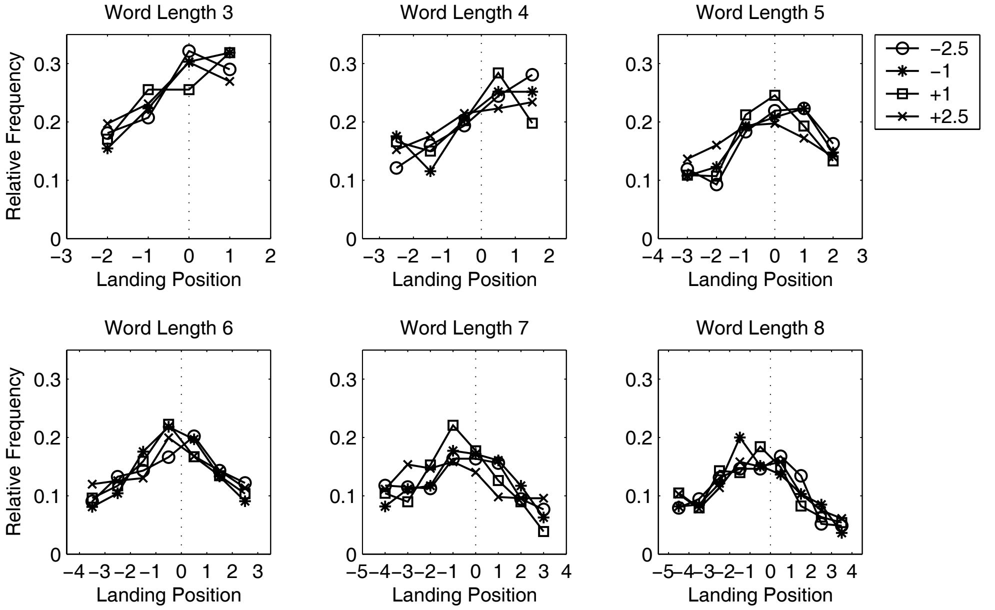

Fig. 4.15 Reading with recurrent sentence shifts experiment. Landing position distributions for saccades following displacement saccades as a function of word length and shift condition. Computations are based on the current coordinates. Each panel represents data for a given word length (3 through 8).

4.5 Summary and Discussion

In Chapter 4, the PVL phenomenon for both progressive (Sec. 4.1, pp. 100) as well as regressive (Sec. 4.2, pp. 102) inter-word saccades could be replicated with data from the original reading experiment (Exp. 1, $N = 245$). There is a considerable variance associated with landing position distributions. Nevertheless, in case of single fixations the maximum of these distributions is somewhat left of word center. For inter-word regressions, the distributions cluster very close to word center.

For empirical landing position distributions, calculated as a function of word length, best-fitting normal curves were computed. Mean and standard deviation of the fitted normal curve characterize the PVL curve and can be used to test hypotheses about changes in the central tendency and variation of landing position distributions as a function of, for example, an experimental manipulation or any other variable being investigated.

As briefly mentioned in the introductory comments on Chapter 4, oculomotor errors form the basis of the generally accepted explanation for the PVL (McConkie *et al.*, 1988). This explanation rests on two premises; first, that saccades are aimed at the center of the target word; and second, that saccades frequently undershoot and sometimes overshoot this functional target location. It should be noted, however, that alternative explanations for the PVL phenomenon have been proposed (see Sec. 7.3.4, pp. 206). McConkie *et al.* (1988) were the first to show that PVL curves are actually composite distributions that can be decomposed by splitting the data by launch site distance. Their assumptions on systematic and random error (see Sec. 7.3, pp. 182) are implemented in both the SWIFT model (Engbert *et al.*, 2005) as well as the E-Z Reader model (Reichle *et al.*, 1999, 2003).

Still, according to the concept of a lexical processing gradient as implemented in the SWIFT model, the left-ward shift of the PVL, when compared with word center as the OVP, could also be *functional* instead of solely being related to oculomotor errors. Lexical processing rate is related to the concept of a visual acuity gradient combined with the phenomenon of a perceptual span. Both to the left and right of the current fixation, there is a rapid drop of visual acuity. However, since both German and English readers read from left to right, the so-called perceptual span extends further to the right than to the left of fixation (e.g. McConkie & Rayner, 1975). Therefore, in the SWIFT model lexical processing rate is assumed to follow an asymmetric Gaussian distribution with different parameters σ_L and σ_R, to the left and to the right of the fixation point, respectively (see Fig. 1 in Engbert *et al.*, 2005).[33] Interestingly, the assumptions on word processing yield a maximum of the processing rate shifted to the left from word center, with this left-shift being stronger for longer words (Fig. 2 in Engbert *et al.*, 2005). Thus, the current concept of lexical processing rates of words is compatible with experimental results on the PVL (Engbert *et al.*, 2005). Note that the issue of theoretical accounts of how PVL and OVP are related will be taken up in the General Discussion (cf., Sec. 9.5, pp. 248).

In Sec. 4.4 (pp. 107), the influence of experimental manipulations on the parameters of the Gaussian PVL function was investigated.[34] When examined across several experimental manipulations, it becomes evident that the “preferred viewing location” is a remarkably stable phenomenon. Leaving the sentence shift experiment aside, there was only one experimental manipulation showing significant effects on the central tendency (*M’*) and spread (*SD*) of the fitted normal distributions: When participants had the head fixed with a bite bar instead of a chin rest only, landing

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[33] $\sigma_L < \sigma_R$.

[34] For both the experimental as well as the control condition, data were again broken down by word length.

position distributions were shifted to the right and had a greater standard deviation. In natural reading, eye movements are frequently accompanied by head movements in reading direction. Working with a chin rest reduces head movements, but they are completely precluded when a bite bar is used. It appears that readers overcompensated for the suppressed head movements in the bite bar condition in that they tended to send their eyes further into the target word than in the less constrained chin rest condition.

No matter what experimental condition, word length had always a significant effect on the mean of the fitted normal landing position distribution, showing as a leftward shift with increasing word length. The word length effect never interacted with experimental condition. The influence of word length on the standard deviation of the fitted normal landing position distributions turned out to be less systematic across experiments.

5 The Fixation-Duration Inverted-Optimal Viewing Position (IOVP) Effect

In Chapter 3 (pp. 62), word center was identified as the optimal viewing position. Furthermore, in Chapter 4 (pp. 100), it was demonstrated that the eyes oftentimes do not land at this optimal position, due to oculomotor error. Chapter 5 and 6 now consider the question how fixation durations "behave" at OVP and/ or across all landing positions.

The work presented in these chapters is strongly motivated by and related to extensive and seminal studies by Vitu *et al.* (2001) and McConkie *et al.* (1988). In their analyses of three large existing corpora of eye movement data (two from adults, one from children), Vitu *et al.* (2001) reported several major viewing position effects. First, Vitu *et al.* provided additional evidence for the *refixation OVP effect*. Second and most interestingly, they found an *Inverted-OVP effect for fixation durations* (IOVP): Single-fixation durations were longer when the eyes were near the center of the word than when the eyes were at the edges of a word; this effect was also found for both the first and the second fixation in two-fixation cases. Third, Vitu *et al.*'s data supported a *trade-off effect* of fixation durations for two-fixation cases which was first found by O'Regan and Lévy-Schoen (1987) for words presented in isolation: When two successive fixations occur on a word there is a tendency for the duration of the initial fixation to be longer, and for the duration of the second fixation to be shorter, the closer the initial fixation lies toward the center of the word.

The experimental evidence on the existence of IOVP effects is currently unclear. In a short commentary, Hyönä and Bertram (2003) reported a replication of the IOVP effect for first fixations. On the contrary, results by Rayner *et al.* (1996) showed relatively flat curves for single fixations (Fig. 4, right column). Similarly, Vitu *et al.* (1990) demonstrated that when reading text, as opposed to isolated words, the gaze durations on words were relatively flat across landing positions. Given the conflicting evidence, Rayner, Pollatsek and Reichle (2003), in their response to a commentary by Vitu (2003), argue that "it seems reasonable to conclude that there isn't a systematic effect of landing position on fixation times" (p. 512).

From a theoretical perspective, IOVP effects are a challenge to current theories of eye-movement control in reading. Particularly bothersome is the IOVP effect for single fixations because neither oculomotor nor cognitive models predict this effect. On the one hand, the IOVP effect for single fixation durations is inconsistent with O'Regan's (1990, 1992) strategy-tactics model. According to this model, the eyes' initial landing position in a word largely determines where the following fixation is made. A second important characteristic of the model is the constant-time assumption, that is processing of a word is assumed to require a constant amount of time irrespective of the fixation position within the word. O'Regan proposed that readers adopt a global strategy (e.g., careful or risky reading) that coarsely influences fixation times and saccade lengths. He also proposed that readers implement local, within-word tactics that are based on lower level, nonlexical information available early in a fixation. If the eyes land in a region of a word that is optimal (near the word's center), there will be a single fixation. In this case, the eyes remain at this location until the word is identified – for a duration that is constant and independent of the fixation location. The constant-time assumption also predicts a flat curve for the gaze duration in two-fixation cases.

Cognitive models provide explicit testable and quantitative predictions concerning many different aspects of eye-movement control. As an example, Reichle *et al.* (1999, 2003) assumed that the lexical processing rate is adjusted by a factor representing eccentricity x, i.e. the distance between the current fixation location and the center of the word being processed: duration(x)=$\text{duration}_0 * \varepsilon^x$, Eq. (4) in Reichle *et al.* (1999), where $\varepsilon > 1$ is a constant. As a result, the E-Z Reader model would predict a U-shaped relation for fixation durations as a function of landing position.

In summary, the explanation for the IOVP effect has been elusive. Vitu *et al.* (2001) considered several reasonable oculomotor and cognitive hypotheses in post-hoc analyses. For example, they tested a saccade length explanation and extensively examined a possible confounding effect of word frequency. They also tested a peripheral preview explanation by reasoning that fixations at the center of the word might be preceded by longer launch site distances. However, they did not find empirical support for their hypotheses. Finally, they settled on a 'perceptual economy strategy' principle that states that "the perceptuo-oculomotor system learns to produce longer fixations at locations where greater information is anticipated, based on prior experience" (p. 3531). The main goal of the thesis was to propose and test a new explanation for the Fixation-Duration IOVP effect (see Chapter 6, pp. 141).

This requires, however, that further empirical evidence for the existence of Fixation-Duration IOVP Effects is provided (Sec. 5.1). Extending the work by Vitu *et* *al.* (2001), a mathematical description is provided. Furthermore, the influence of experimental manipulations on the IOVP function is investigated (Sec. 5.2, pp. 132).

5.1 IOVP Effects in Continuous Reading

5.1.1 Single Fixations

Based on data from the original reading experiment (Exp. 1, $N = 245$), the effect of initial landing position on mean single fixation duration was investigated. Durations shorter than 30 ms or longer than 1 s were excluded from analyses. The current data replicate Vitu *et al.*'s (2001) Inverted-OVP effect for single fixations (Fig. 5.1), reflected in the inverted U-shapes of fixation durations as a function of the initial landing position within a word. Across different word lengths, fixation durations were longer when the eyes landed in the middle of a word than when they landed near the end of the word.

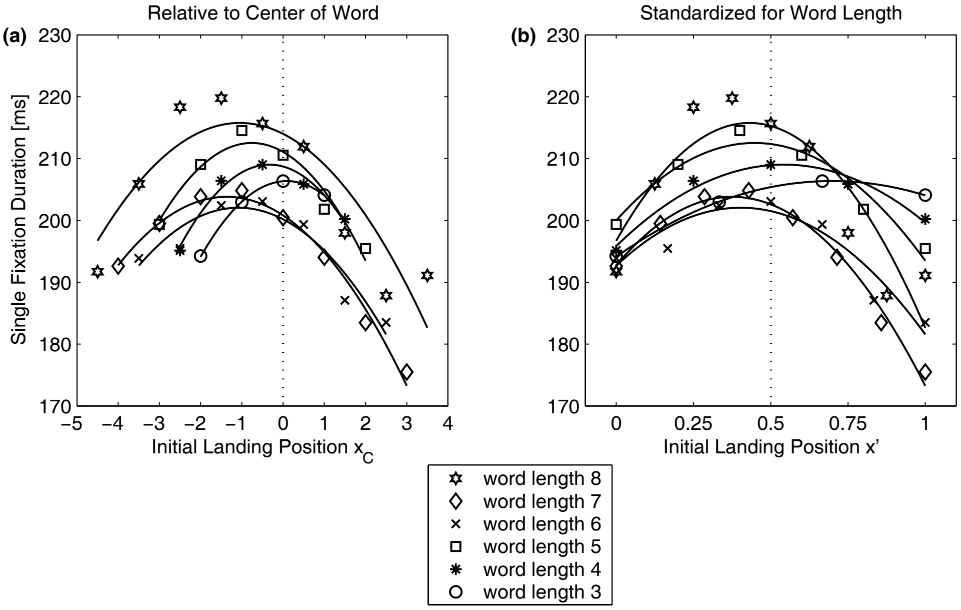

Fig. 5.1 Mean single fixation duration as a function of word length and initial landing position within a word, for 3- to 8-letter words. (a) The initial landing position in the word is plotted as letter position relative to the center of the word. (b) Landing position is standardized. In both panels, the dotted vertical line represents the center of the word.

To estimate the IOVP effect quantitatively, the effect was approximated with the same quadratic polynomial as in Eq. (1) (p. 63), where y is now fixation duration and the slope parameter B is negative due to the inverted parabolic relationship. Estimates of

A, *B*, and *C* are presented in Table 5.1. Across all word lengths, the maximum was within 1.2 letter positions left of word center. Thus, the maximum fixation duration *A* was located only slightly left of OVP as determined by refixation curves (cf., Table 3.1, p. 64), which is consistent with the interpretation of *C* as OVP. Parameter *B* again indicated the slope of the curve, now reflecting the "benefit" for not fixating at OVP.

Table 5.1 Quadratic fit of IOVP curves for single fixation durations: Estimates of parameters *A*, *B* and *C*. Note. *CC* = *C* - Center of Word. χ^2 denotes sum of squared residuals.

WORD LENGTH	CENTER OF WORD	SINGLE FIXATION DURATIONS							
		A	*B*	*B'*	*C*	*CC*	*C'*	χ^2	*N*
3	2	211	-4.7	-42	1.9	-0.1	0.63	0.7	22769
4	2.5	211	-3.3	-53	2.08	-0.42	0.52	2.6	16606
5	3	214	-2.7	-68	2.2	-0.8	0.44	23.04	18981
6	3.5	203	-1.6	-58	2.44	-1.06	0.41	40.32	16983
7	4	204	-1.6	-78	2.68	-1.32	0.38	31.49	14776
8	4.5	216	-1.6	-102	3.43	-1.07	0.43	277.18	10340

For each participant, an empirical Single-Fixation IOVP curve was computed and fitted to the quadratic function.[35] The 3 parameters were then averaged across all participants. For each word length, parameter *B* differed significantly from 0 [$t(225) > 16.5$, $p < 0.001$], corroborating the quadratic trend of fixation durations across landing positions. In addition, the influence of word length on the parameters of the quadratic function was examined. Again, this required the landing position axis to be standardized for word length (see Fig. 5.1b; cf., Sec. 3.1, pp. 62). Thus, parameters *B* and *C* were transformed to $B' = B \cdot L^2$ and $C' = C/L$. The transformed values for *B'* and *C'* are listed in Table 5.1. Parameter *A* was not affected by these transformations. Interestingly, the behavior of parameter *B'* changed with the transformation: Whereas the absolute value of *B* decreased across word lengths, *B'* systematically increased. This indicates that the strength of the IOVP effect increased (rather than decreased) with word length.

Parameters *A*, *B'*, and *C'* characterize the Fixation-Duration IOVP effect. The parameters were used as dependent variables in ANOVAs with word length as within-

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[35] For statistical analyses, 19 out of 245 participants were excluded because they had contributed less than 100 valid sentences to the data base, cf., Sec. 2.1.5 (p. 21).

subject factor. Word length had a significant effect on all three parameters. Parameter *A* increased with increasing word length [$F(5,221) = 76.52$, $MSE = 708.3$, $p = .000$, $\eta^2 = .254$]. With increasing word length, there was a slight leftward shift associated with parameter *C'* [$F(5,221) = 90.57$, $MSE = 27719.4$, $p = .000$, $\eta^2 = .287$]. Furthermore, the strength of the IOVP effect increased with word length [parameter *B'*: $F(5,221) = 12.46$, $MSE = .093$, $p = .000$, $\eta^2 = .052$]. Moreover, both linear and quadratic trends were consistently significant.

5.1.2 Two-Fixation Cases

The following analyses consider cases were exactly two fixations occurred on a word. Note that these refixation cases are not very frequent. Therefore, no statistical analyses were undertaken because there were not enough data per subject or word available. Data presented in this section were averaged across all participants.

For the first of two fixations there is a distinct IOVP effect (Fig. 5.2a), which is somewhat less pronounced for the second of two fixations (Fig. 5.2b). It appears that the IOVP effect is considerably stronger for first fixations (Fig. 5.2a) as compared to single fixations (Fig. 5.1).

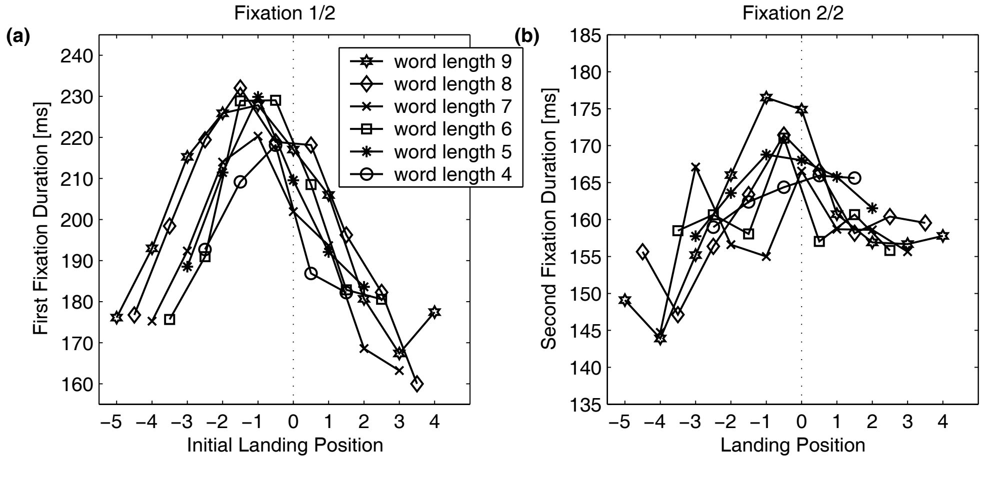

Fig. 5.2 Two-fixation cases. IOVP effect for first (a) and second (b) fixation durations. Different than in Fig. 5.5, the duration of the second fixation is plotted as a function of its own landing position.

The IOVP curves presented in Fig. 5.2 can be further decomposed by a separate consideration of forward refixations (Fig. 5.3) vs. backward refixations (Fig. 5.4). The fixation preceding a forward refixation as well as the fixation preceding a backward refixation contribute to the IOVP effect for first fixation durations (Fig. 5.2a). For forward refixations, almost all first fixations are located left of word center (Fig. 5.3a) while for backward refixations, the majority of first fixations are located right of word center (Fig. 5.4a).[36] Therefore, for the first fixation duration IOVP effect (Fig. 5.2a) it is concluded that the main contribution to the rising left branch comes from forward refixations while the falling right branch almost exclusively stems from backward refixations. Roughly, this logic also holds for the IOVP effect for second fixation durations.

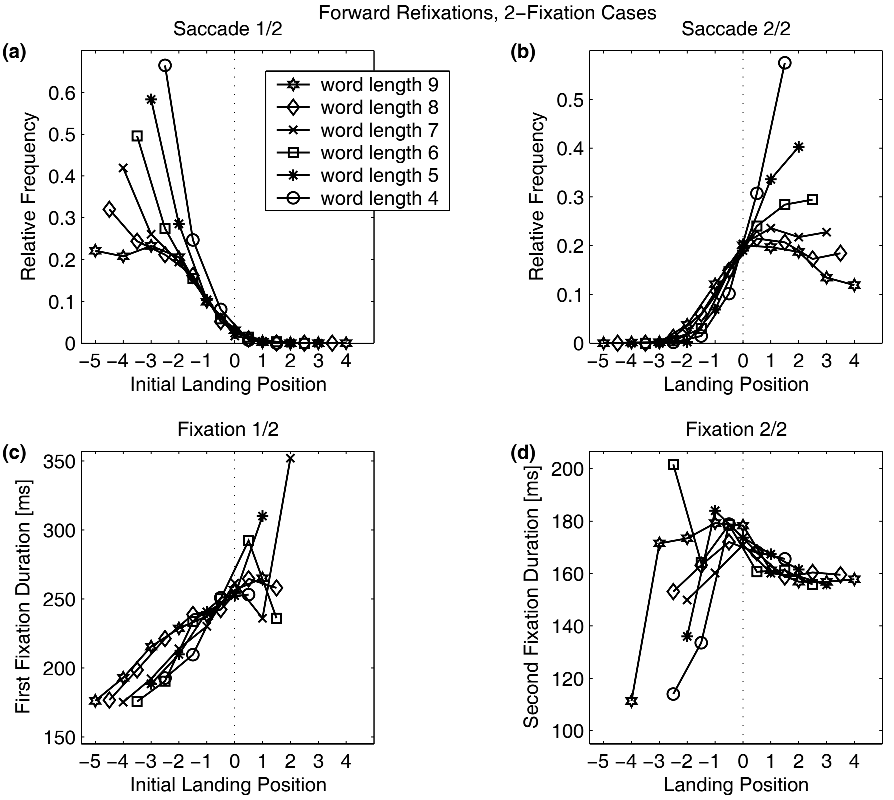

Fig. 5.3 Two-fixation cases, forward refixations, 4- to 9-letter words. Landing position distribution for first (a) and second (b) saccades into a word; the second saccade is the refixation saccade. IOVP effect for first (c) and second (d) fixation durations.

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[36] Note, however, that – at least for younger readers – forward refixations are more frequent than backward refixations.

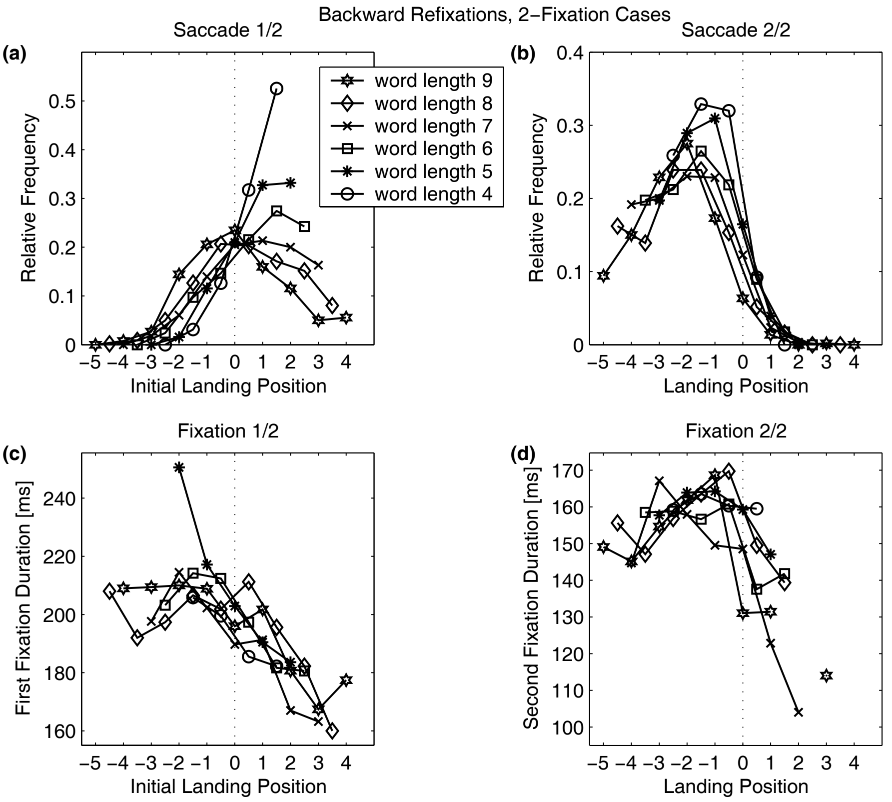

Fig. 5.4 Two-fixation cases, backward refixations, 4- to 9-letter words. Landing position distribution for first (a) and second (b) saccades into a word; the second saccade is the refixation saccade. IOVP effect for first (c) and second (d) fixation durations.

An interesting phenomenon can be observed when both the first and the second fixation duration is plotted as a function of first fixation position (Fig. 5.5): While the duration of the first fixation exhibits the IOVP effect, the opposite pattern is apparent for the second fixation duration (O’Regan & Lévy-Schoen, 1987; Vitu *et al.*, 2001). Second fixation duration is shortest when the initial fixation is at word center, and longest when the first fixation is near word beginning or word ending; thus, the second fixation duration appears to “trade-off” against the first. O’Regan and Lévy-Schoen (1987), first reporting this trade-off effect, postulated that a constant amount of time is required for processing a word. Thus, the amount of processing time spent on the word during the first fixation is saved during the second fixation. However, Vitu *et al.* (2001) alternatively argued that the fixation-duration trade-off effect in two-fixation cases results from the fact that the IOVP effect is found for both first and second fixation durations, combined with the statistical fact that initial fixations near the center of a word (which tend to be longer) are more likely to be followed by a fixation toward one end (which tend to be shorter), and vice versa.

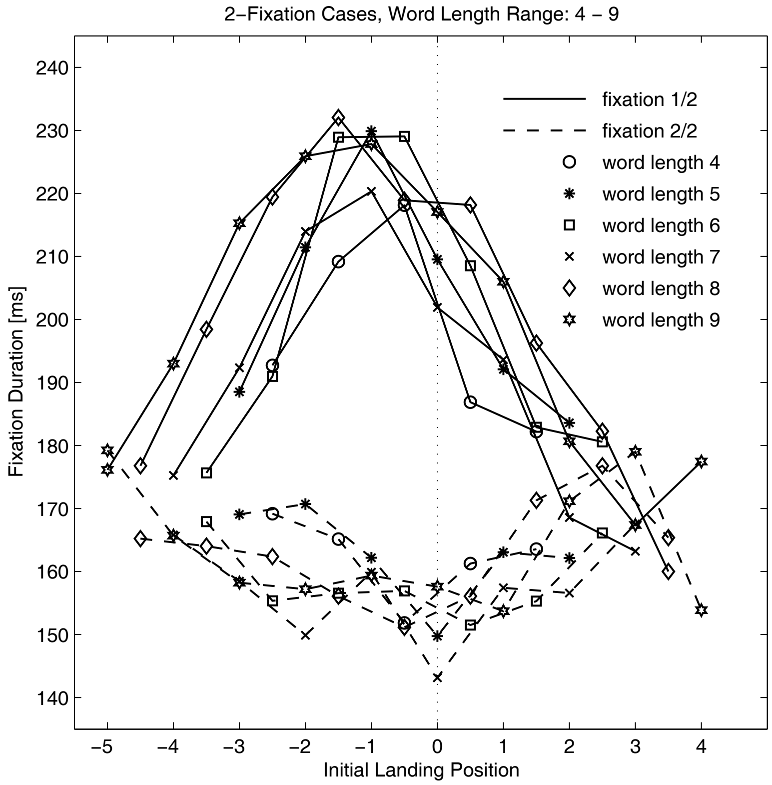

Fig. 5.5 Mean duration of first and second fixations in the cases where the eyes made exactly two fixations on a word as a function of the initial fixation position in the word, for 4- to 9-letter words. Data for the first of two fixations correspond to Fig. 5.2a.

5.1.3 Gaze Durations

Finally, the effect of initial fixation position on gaze durations was investigated (i.e., the sum of initial fixation and all refixations on a word before the eyes move on to another word, see Fig. 5.6). Roughly, gaze-duration curves were a result of the refixation OVP effect and the IOVP effects for single and first (and 2+) fixations. While refixation probability is lowest at word center, it is higher for initial fixations at the beginning of the word than for initial fixations at the end of a word (see Fig. 3.1, p. 63). In addition, durations of fixations at the end of words were somewhat shorter than those at the beginning (see Fig. 5.1). Therefore, we observed rudimentary U-shaped curves for gaze durations with a decreasing trend across fixation positions (see Fig. 5.6).

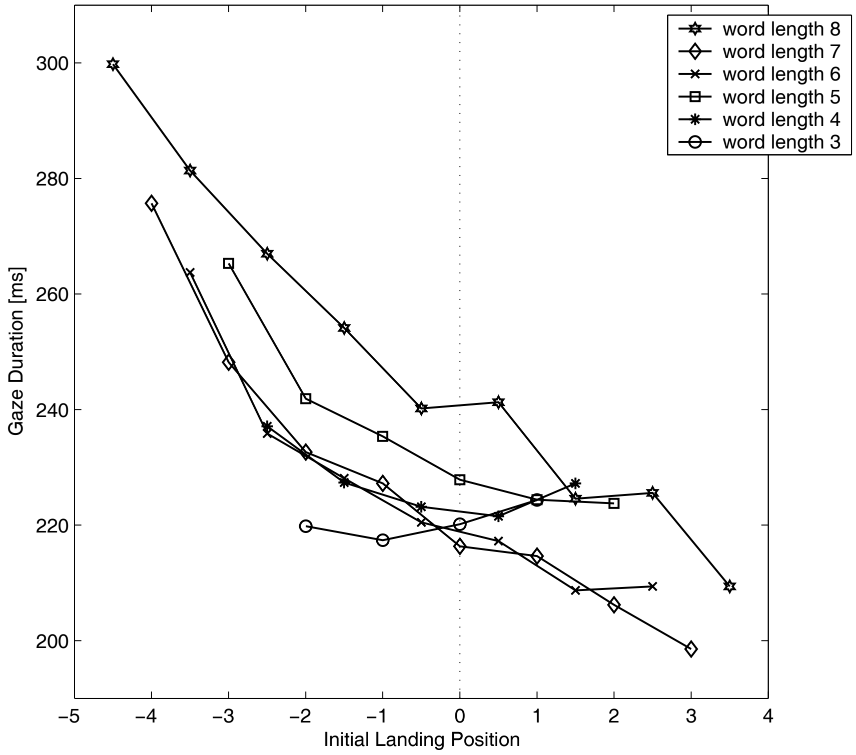

Fig. 5.6 Mean gaze duration as a function of the initial landing position within a word, for 3- to 8-letter words.

5.1.4 Word Center as the Optimal Viewing Position

The results indicate that fixating the word center decreases refixation probability but increases fixation duration. The word center can still be interpreted as the optimal viewing position, since the costs of programming a refixation are much greater (more than 100 ms) than the size of the IOVP effect (20 to 40 ms). Table 5.2 explores this argument in more detail. Experiments in which subjects moved their eyes to visual targets indicated that the saccadic latency, or the time needed to program and execute a saccade, is approximately 180 to 250 ms (Becker & Jürgens, 1979). Even if uncertainty about when or where to move the eyes was eliminated, saccade latency was at least 150 to 175 ms (Rayner, Slowiaczek, Clifton, & Bertera, 1983). It is suspected that the latency for refixation saccades would have to be placed at the lower end of this range. Therefore, the time needed to program a refixation saccade was set to τ_R=150 ms. Furthermore, for simplicity it was assumed that C_R = 0 for both OVP and IOVP analyses. For every word length L and every landing position x, the average cost R for programming a refixation was then computed by applying Eq. (1) as

$$R = \tau_R \,(A_L + B_L (x - x_0)^2), \tag{2}$$

where x_0 is the word center. The refixation costs were contrasted with the gain G of not carrying out a refixation while not fixating word center. This was done by using the parameters of the IOVP effect for single fixation durations,

$$G = B_L (x - x_0)^2 \tag{3}$$

To give a numerical example, let us consider a 7-letter word that is initially fixated on the first letter. Numerical values for A_7, B_7, and x_0 from Table 3.1 (p. 64) yield an increase of gaze duration of 32.6 ms [= $150(0.073 + 0.016(1–4)^2)$]. Conversely, the single fixation duration “benefit” for not fixating the center of word only amounts to 14.4 ms [= $1.6(1–4)^2$ with B_7 from Table 5.1]. For all word lengths and landing positions, refixation costs are larger than the duration “benefits”. This analysis provides strong support for the hypothesis that the word center represents the optimal viewing position.

Table 5.2 Refixation costs R [ms] and single fixation duration gain G [ms] as a function of landing position for different word lengths

WORD LENGTH	**LANDING POSITION**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
3	Refixation cost R (ms)	23.7	12.5	8.7	12.5	0	0	0	0	0
	Duration gain G (ms)	18.8	4.7	0	4.7	0	0	0	0	0
4	Refixation cost R (ms)	32.4	15.6	7.2	7.2	15.6	0	0	0	0
	Duration gain G (ms)	20.6	7.4	0.8	0.8	7.4	0	0	0	0
5	Refixation cost R (ms)	42.3	24.3	13.5	9.9	13.5	24.3	0	0	0
	Duration gain G (ms)	24.3	10.8	2.7	0	2.7	10.8	0	0	0
6	Refixation cost R (ms)	42.4	26.2	15.4	10	10	15.4	26.2	0	0
	Duration gain G (ms)	19.6	10	3.6	0.4	0.4	3.6	10	0	0
7	Refixation cost R (ms)	49.4	32.6	20.6	13.4	10.9	13.4	20.6	32.6	0
	Duration gain G (ms)	25.6	14.4	6.4	1.6	0	1.6	6.4	14.4	0
8	Refixation cost R (ms)	61.3	44.5	31.9	23.5	19.3	19.3	23.5	31.9	44.5
	Duration gain G (ms)	32.4	19.6	10	3.6	0.4	0.4	3.6	10	19.6

5.2 Influence of Experimental Manipulations on Parameters of the IOVP Function

In the previous section, the existence of several Fixation-Duration IOVP effects could be established for the original reading experiment (Exp. 1, $N = 245$). In the present section, it is examined whether different experimental manipulations influence the parameters of the quadratic IOVP function.

For statistical analyses, plots, and tables, a word-length dependent empirical IOVP curve was computed for each participant, as well as a quadratic fit to that curve. To ensure stable participant-based curves showing the characteristic inverted U-shape, computations were based on *all* reading fixations except the first and last fixations in a sentence, and fixations being shorter than 30 ms or longer than 1000 ms. Parameters A, B', and C' of the fitted quadratic function characterize the Fixation-Duration IOVP effect. For figures displaying empirical IOVP curves, the individual empirical IOVP curves were averaged across participants. For illustrational purposes, a quadratic function was again fitted to these averaged IOVP curves.[37] For figures displaying fit parameters as a function of word length, the values obtained for each individual were averaged across participants. In this way, the weights of individual subjects' contributions to the final values were not influenced by the number of fixations that qualified for a particular condition. Participants who contributed less than 100 (out of 144) valid sentences were excluded from analyses. Analyses of variance were run on the three parameters of the fitted quadratic function, with the parameters obtained for each participant in each word length condition.

5.2.1 Results from *Z* String "Reading" Experiment (Exp. 2)

The *z* string "reading" experiment is an oculomotor control condition to the original reading experiment (Exp. 1) because no higher level lexical, semantic, or syntactic processes are involved. Interestingly, in a prior research report, for *z* strings there was no effect of landing zone on single fixation duration (Rayner & Fischer, 1996). Results from the current study, however, clearly show that the IOVP effect also exists in "mindless reading" (Fig. 5.7).

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[37] Thus, the fit was not based on parameter values that were averaged across participants.

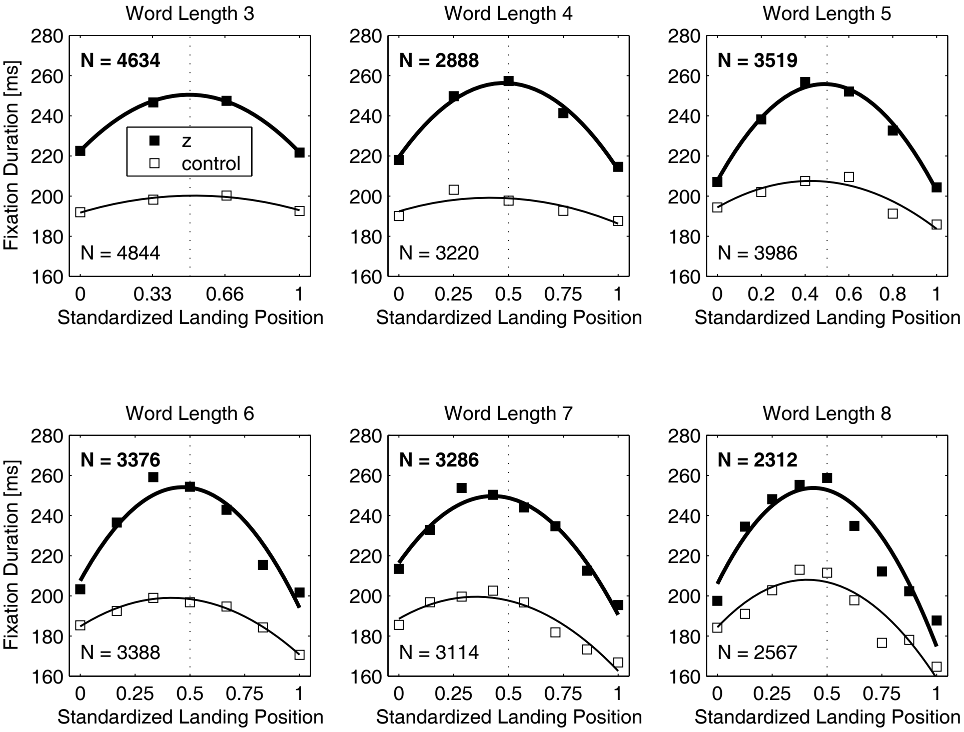

Fig. 5.7 *Z* string “reading” data (full squares) vs. “normal” reading control data (open squares). Mean fixation duration as a function of word length and standardized initial landing position within a word, for 3- to 8-letter words. Also presented is the best fit to $y = A - B(x - C)^2$.

When the parameters *A*, *B’*, and *C’* of the fitted quadratic function are considered it becomes clear that in the *z* string “reading” condition, both *A* as well *B’* are considerably higher than for the control data (Fig. 5.8, see also Appendix P, Table P1).

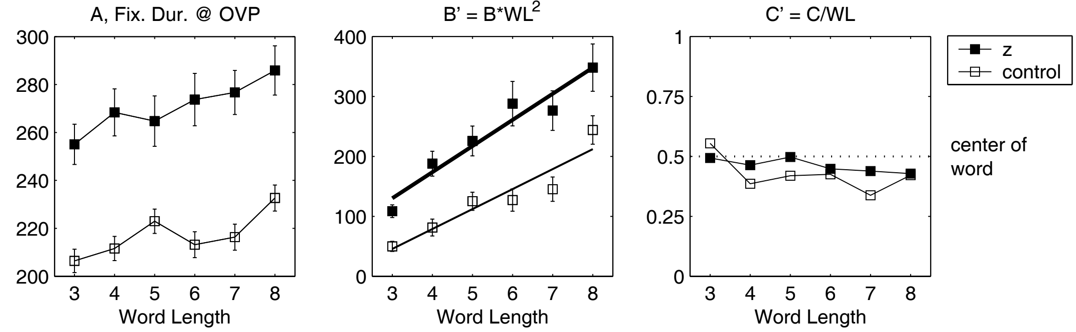

Fig. 5.8 Fixation-Duration IOVP effect for *z* string “reading” data (full squares) vs. “normal” reading control data (open squares). Empirical data were fitted to $y = A - B(x - C)^2$. Comparison of parameters of the quadratic function.

To test the statistical significance of these observations, for each of the three parameters, a 2 × 6 repeated measures ANOVA with “experimental condition” and “word length” as within-subject factors was conducted. As suggested by Fig. 5.8, both *A* [$F(1,30) = 36.70$, $p = .000$] as well as *B’* [$F(1,30) = 24.79$, $p = .000$] were significantly increased in the *z* string “reading” condition. In addition, for all three parameters there was a significant word length effect (see Appendix Q, Table Q1).

Taken together, the IOVP effect is stronger in *z* “reading” than in “normal” reading, as reflected in parameter *B’*.

5.2.2 Results from Reading with Salient OVP Experiment (Exp. 3)

The IOVP effect also emerges in an experimental condition with salient OVP letters (Fig. 5.9; descriptive statistics: Appendix P, Table P2).

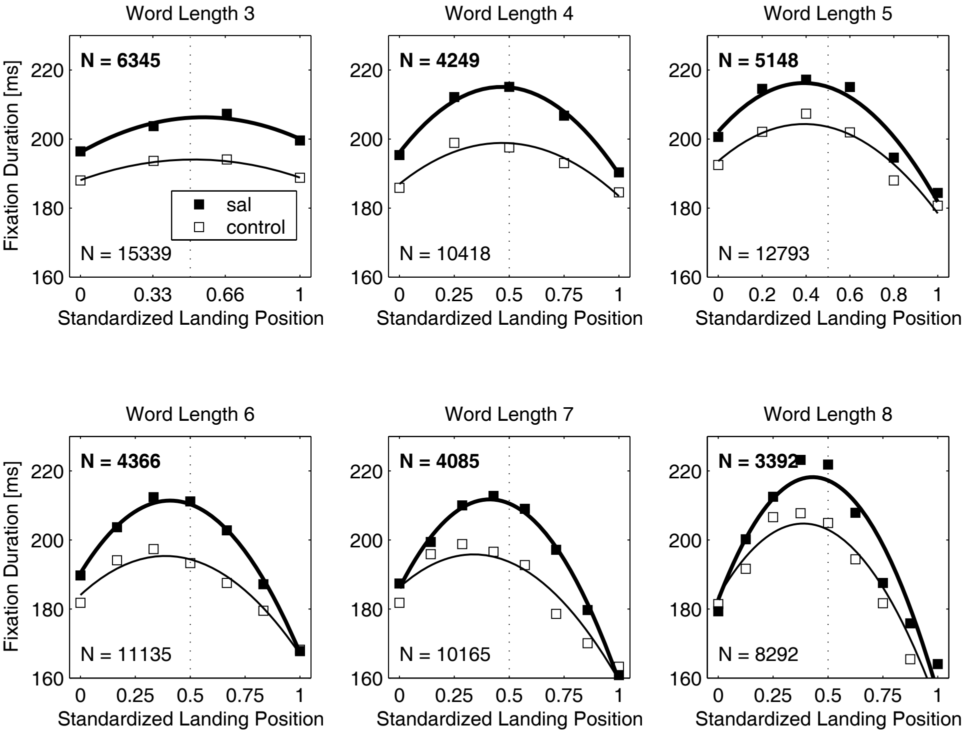

Fig. 5.9 Reading with salient OVP data (full squares) vs. normal reading control data (open squares). Mean fixation duration as a function of word length and standardized initial landing position within a word, for 3- to 8-letter words. Also presented is the best fit to $y = A - B(x - C)^2$.

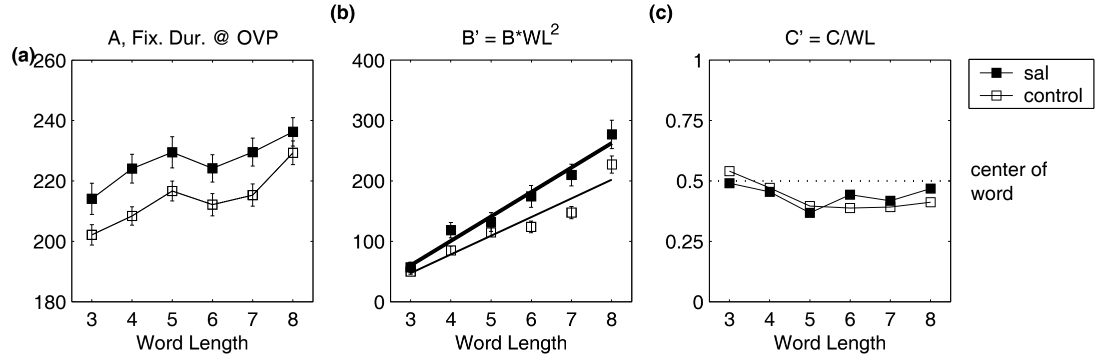

Fig. 5.10 Fixation-Duration IOVP effect for reading with salient OVP data (full squares) vs. normal reading control data (open squares). Empirical data were fitted to $y = A - B(x - C)^2$. Comparison of parameters of the quadratic function.

For each of the three parameters of the fitted quadratic function, an ANOVA with "experimental condition" (reading with salient OVP vs. normal reading) as between-subject factor and "word length" as within-subject factor was employed. Both *A* [$F(1,141) = 4.12$, $p = .044$] as well as *B'* [$F(1,141) = 9.70$, $p = .002$] were significantly increased in the experimental condition (Fig. 5.10). In addition, for all three parameters there was a significant word length effect while none of the "experimental condition" × "word length" interactions were significant (for a complete report see Appendix Q, Table Q2). Taken together, the significant main effect on parameter *B'* suggests that the IOVP effect is stronger in the "reading with salient OVP" condition than in normal reading.

5.2.3 Results from Reading with a Bite Bar Experiment (Exp. 4)

The IOVP effect could also be replicated for an experimental condition where participants' head movements were eliminated by using a bite bar (Fig. 5.11).

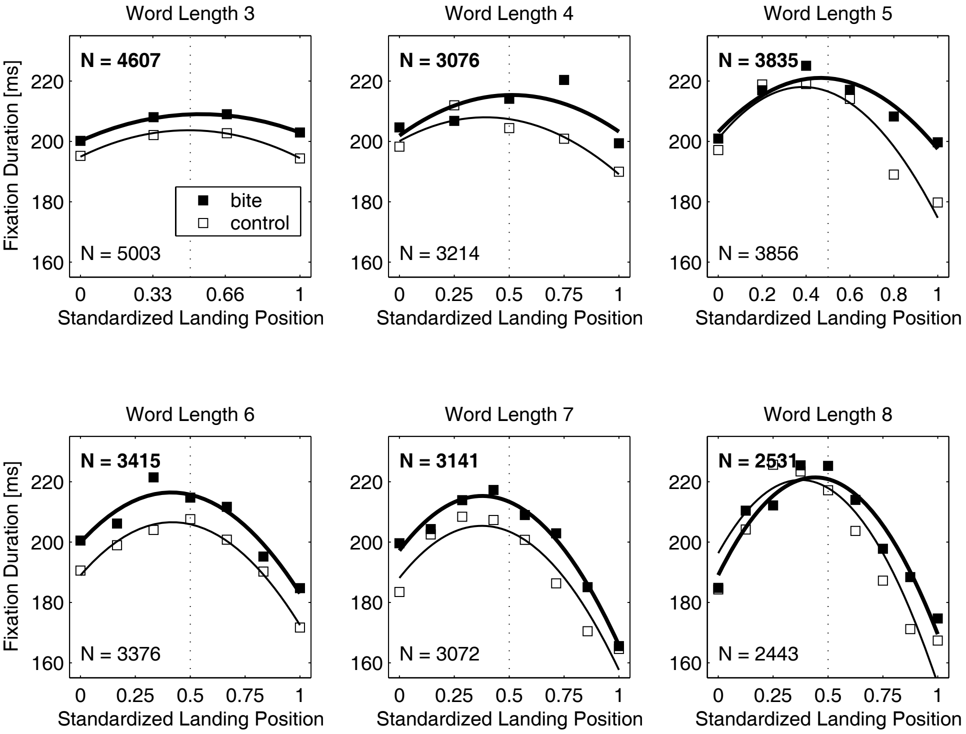

Fig. 5.11 Reading with a bite bar data (full squares) vs. chin rest reading control data (open squares). Mean fixation duration as a function of word length and standardized initial landing position within a word, for 3- to 8-letter words. Also presented is the best fit to $y = A - B(x - C)^2$.

Parameters *A*, *B'*, and *C'*, characterizing the IOVP effect, did not significantly differ when reading with a bite bar was compared with unconstrained reading with a chin rest (Fig. 5.12; descriptive statistics: Appendix P, Table P3; information on statistical analyses: Appendix Q, Table Q3). Again, there were significant word length effects for parameters *A* [$F(5,56) = 25.41$, $p = .000$], and *B'* [$F(5,56) = 33.86$, $p = .000$].

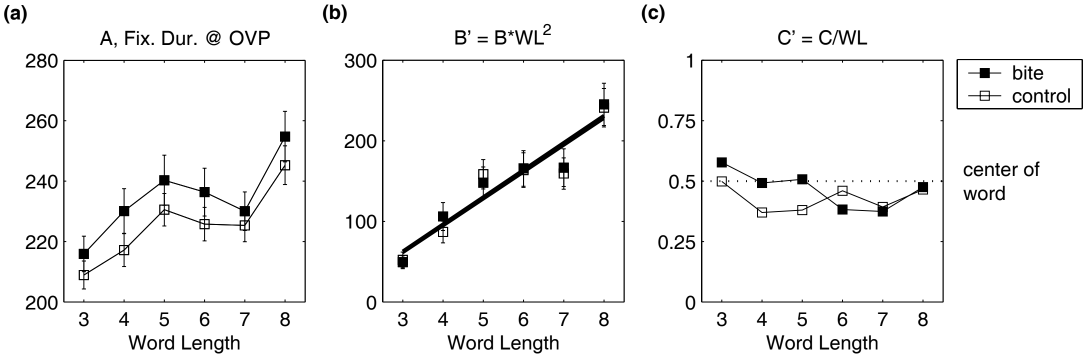

Fig. 5.12 Fixation-Duration IOVP effect for reading with a bite bar data (full squares) vs. chin rest reading control data (open squares). Empirical data were fitted to $y = A - B(x - C)^2$. Comparison of parameters of the quadratic function.

5.2.4 Results from Reading under Low Contrast Experiment (Exp. 5)

Interestingly, the IOVP effect is also found in an experimental condition that had participants read the sentences of the Potsdam Sentence Corpus with low letter contrast (Fig. 5.13; descriptive statistics: Appendix P, Table P4).

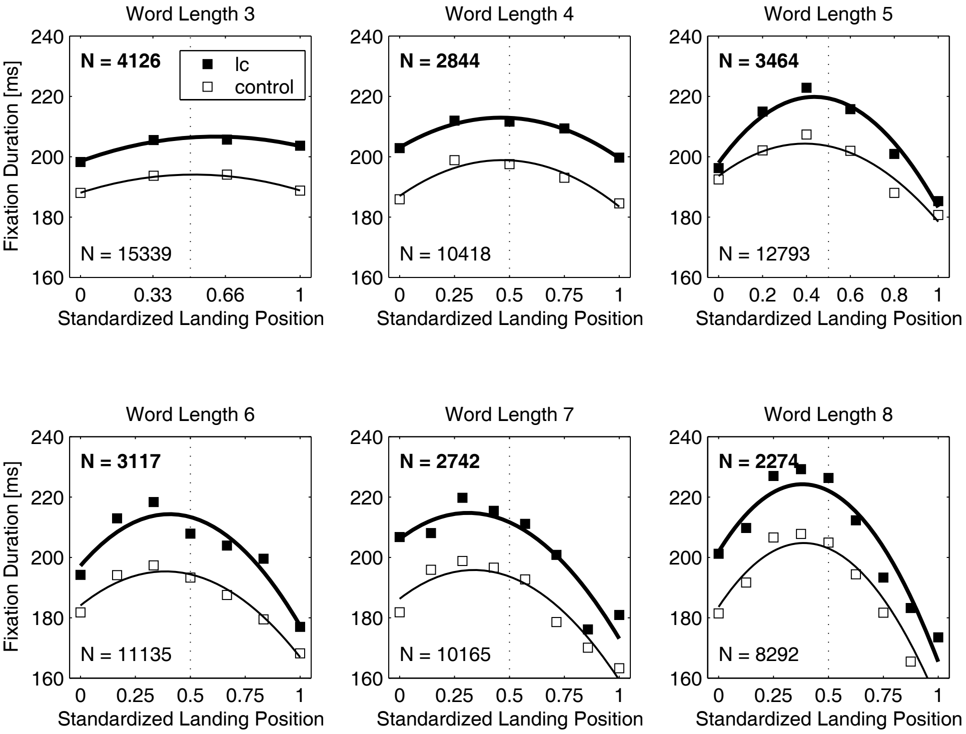

Fig. 5.13 Low contrast reading data (full squares) vs. control data (open squares). Mean fixation duration as a function of word length and standardized initial landing position within a word, for 3- to 8-letter words. Also presented is the best fit to $y = A - B(x - C)^2$.

Only parameter A was systematically affected by letter contrast [$F(1,131) = 7.41$, $p = .007$]; the main effect was accompanied by a significant interaction with word length [$F(5,127) = 3.24$, $p = .010$] (Fig. 5.14). As expected, for all three parameters there was a significant word length effect (see Appendix Q, Table Q4).

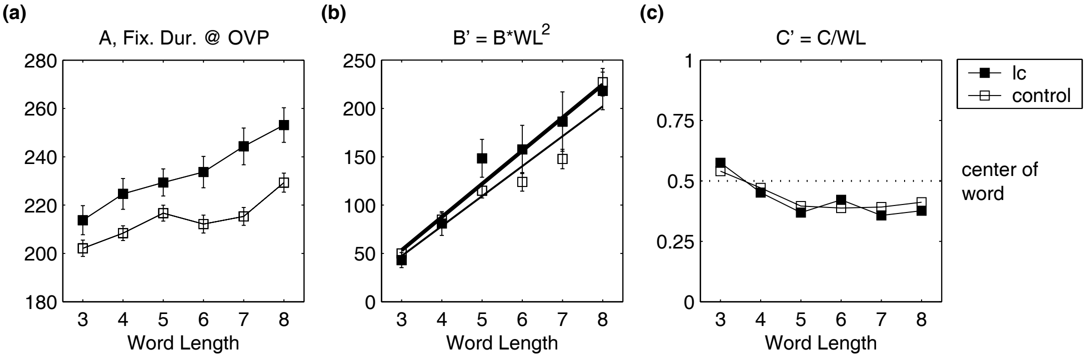

Fig. 5.14 Fixation-Duration IOVP effect for low contrast reading data (full squares) vs. normal reading control data (open squares). Empirical data were fitted to $y = A - B(x - C)^2$. Comparison of parameters of the quadratic function.

Thus, the IOVP effect is not stronger in the low contrast reading condition. Rather, the IOVP function is simply vertically displaced upward, as reflected in higher values for parameter *A* indexing the maximum of the curve.

Note that data from the reading with recurrent sentence shifts experiment (Exp. 6) will be considered in Sec. 6.4, pp. 166.

5.3 Summary and Discussion

Based on the analysis of data from the original reading experiment (Exp. 1, $N = 245$), Vitu *et al.*'s (2001) Fixation-Duration IOVP effects were replicated for both single, first, and second fixations (Sec. 5.1, pp. 124). Fixations were longer when the eyes landed near the center of the word than when the eyes landed at the edges of a word. It is noteworthy that the IOVP effects were relatively large effects, producing differences in fixation durations of 20 to 40 ms for single fixations, and up to 80 ms for first fixations.

Extending the pioneering work by Vitu *et al.* (2001), a better mathematical description of the IOVP effect was provided by fitting the data to a quadratic function, i.e. a polynomial of second order (Eq. 1, p. 63). Parameter *A*, the vertical offset of the curve, reflects the fixation duration maximum. Parameter *C'*, the horizontal offset of the curve, reflects the fixation position within a word where this maximum is reached. Finally, parameter *B'*, the slope of the quadratic function, quantifies the "benefit" of not fixating at OVP. The three parameters can be used to describe, test, and interpret changes on the IOVP curve as a function of word length, an experimental manipulation or any other variable under investigation.

Based on the data from the original reading experiment (Exp. 1), it was demonstrated that the strength of the experimentally obtained IOVP effect for single fixations increases with word length, a finding that is compatible with the mechanism assumed to be responsible for the effect (see Chapter 6 below). It is interesting to note that further analyses based on data from Exp. 1 showed that the IOVP effect is obtained even with simultaneous statistical control for a large number of other well-known influences on fixation durations (Kliegl *et al.*, 2006).

In Sec. 5.2 (pp. 132), the influence of experimental manipulations on the parameters of the inverted U-shaped IOVP function was investigated.[38] The summary of the bite bar reading data (5.2.3) is done quickly because none of the three parameters was significantly affected by the manipulation.

Parameter *A* was significantly increased by both the letter contrast manipulation (5.2.4), by reading with salient OVP (5.2.2), as well as in the *z* string "reading condition" (5.2.1), but not in the bite bar reading condition (5.2.3). None of the experimental manipulations, however, significantly affected parameter *C'*, the within-word location of maximum fixation duration *A*. At first, the effect on *A* simply and roughly reflects the effect of experimental manipulation on fixation duration as such (see Chapter 2 with global analyses of experiments). The current analyses, however, give a more detailed picture by bringing the slope of position-dependent duration curves into the game.

In the low-contrast reading condition, parameter *B'*, as *C'*, was not affected by the experimental manipulation. The effect on *A* therefore translates into a vertical upward displacement of the Fixation-Duration IOVP curves: At each fixation position, fixation durations were equally increased.

When the OVP of certain words was marked, however, not only *A* but also parameter *B'* was significantly higher for the experimental than the control data. This finding suggests that participants did not only produce longer fixation durations as such; rather, durations were especially long when fixating at word center. This is an interesting finding which is compatible with the way the word material was prepared in the saliency reading experiment (see Sec. 2.3, p. 33). Three-letter words were never marked. About 50 percent of 4-letter words were marked, while the other half was not. For word lengths 5-10, there were always more marked than unmarked words. Interestingly, for 3-letter words the IOVP curve was simply vertically displaced (Fig.

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[38] For both the experimental as well as the control condition, data were again broken down by word length.

5.9, p. 134). Only for longer word lengths, where marked words outnumbered unmarked words, the increased *A* parameter was accompanied by a stronger curvature of the IOVP function. Earlier global analyses showed that fixation durations were globally inflated in the saliency reading condition. The current analyses specify that finding in that they suggest that fixation duration was especially prolonged when readers fixated around word center. Apparently, they stayed longer on the word when the OVP could be easily isolated.

As in the reading with salient OVP, both parameters *A* as well as *B'* were significantly increased when participants read the *z* string version of the Potsdam Sentence Corpus as compared to the normal version. The results for the *z* string "reading" data as well as the reading with salient OVP experiment will be further discussed in the General Discussion (Sec. 9.2.3, pp. 229), because the data are relevant for the explanation of IOVP effects, as developed in the next chapter.

Last but not least, replicating the general pattern obtained in Sec. 5.1.1 (p. 124) for single fixation durations in the original reading experiment (Exp. 1, $N = 245$), word length had always a significant effect on both parameters *A* as well as *B'*, no matter what experimental condition considered. Apart from the bite bar reading condition, there was also a consistently significant word length effect on parameter *C'*.

Fitting the empirical IOVP curves to a quadratic function with three parameters allows a more detailed description and interpretation of factors modulating the Fixation-Duration IOVP effect. The goodness of fit was very good when individual empirical IOVP curves were averaged across participants and this averaged empirical curve was then fitted to a quadratic function (see, e.g., Fig. 5.7, p. 133). The fitting procedure turned out to be somewhat less promising when participant-based empirical IOVP curves were fitted. Because of interindividual differences and data power problems, the goodness of fit was usually poorer. As a result, mean values for parameters *A* and *B'* were higher when participant-based obtained parameters were averaged across participants than when individual empirical IOVP curves were averaged across participants and then fitted to a quadratic function (e.g., compare Fig. 5.7 with Fig. 5.8 and/or Table P1 in Appendix P).

6 Modeling the Fixation-Duration Inverted-OVP Effect

The theoretical heart of this thesis is the introduction of a new explanation for the puzzling IOVP effect. The here proposed mechanism underlying the IOVP effect expands on the consequences of saccadic errors (see Chapter 4, pp. 100). Not only does the combination of systematic and random error lead to undershoots or overshoots of the center of the intended target word, it also produces saccades that land on unintended words (McConkie *et al.*, 1988). A central goal of this chapter is to introduce an algorithm for estimating the proportion of these *mislocated fixations* from empirical data (Sec. 6.1.2). In addition, it is suggested that IOVP effects are a consequence of mislocated fixations (Sec. 6.1.3). For validation, the proposed IOVP model is applied to the *z* string "reading" data which serve as an oculomotor control condition (Sec. 6.2). Furthermore, simulations with the SWIFT model (Sec. 6.3) as well as data from the sentence-shift experiment (Sec. 6.4) give further insight into the proposed mechanisms.

6.1 IOVP Effects as a Consequence of Mislocated Fixations Caused by Saccadic Errors

The analysis to check the hypothesis that saccade-error correction underlies the IOVP effect was performed in three steps. First, the parameters of normal distributions for landing positions were estimated (Sec. 6.1.1). Second, the probability for mislocated fixations was calculated as a function of landing position, based on the overlap of landing position distributions to neighboring words (Sec. 6.1.2). Third, the assumption that an error-correction of mislocated fixations reproduces the IOVP was tested quantitatively (Sec. 6.1.3).

6.1.1 Landing Position Distributions

It is a well-established result that locations of initial fixations on a word of a given length are approximately normally distributed, with the mean of the distribution falling slightly to the left of the center of the word (i.e., the preferred viewing location; see Chapter 4, pp. 100).

Potentially, all types of fixations (i.e., not only initial fixations) can contribute to mislocated fixations. Therefore, landing position distributions were re-computed, now based on *all* fixations except the first and last fixation in a sentence (Fig. 6.1). Landing position distributions reported in the literature are typically based on initial fixations only (e.g., McConkie *et al.*, 1988; Rayner *et al.*, 1996; Vitu *et al.*, 2001), yet the preferred viewing location phenomenon is replicated in the current data which are based on both initial fixations, refixations and regressions.[39] In comparison with the optimal viewing position (Fig. 3.1, p. 63), the preferred viewing location was slightly shifted to the left (O'Regan & Lévy-Schoen, 1987).

Note that when *all* fixations are considered (Fig. 6.1, Table 6.1), results are similar to results for *single* fixations (Fig. 4.1, p. 101; Table 4.1, p. 101). Interestingly, however, estimated standard deviations (ca. 2.2) were now largely independent of word length (Table 6.1).

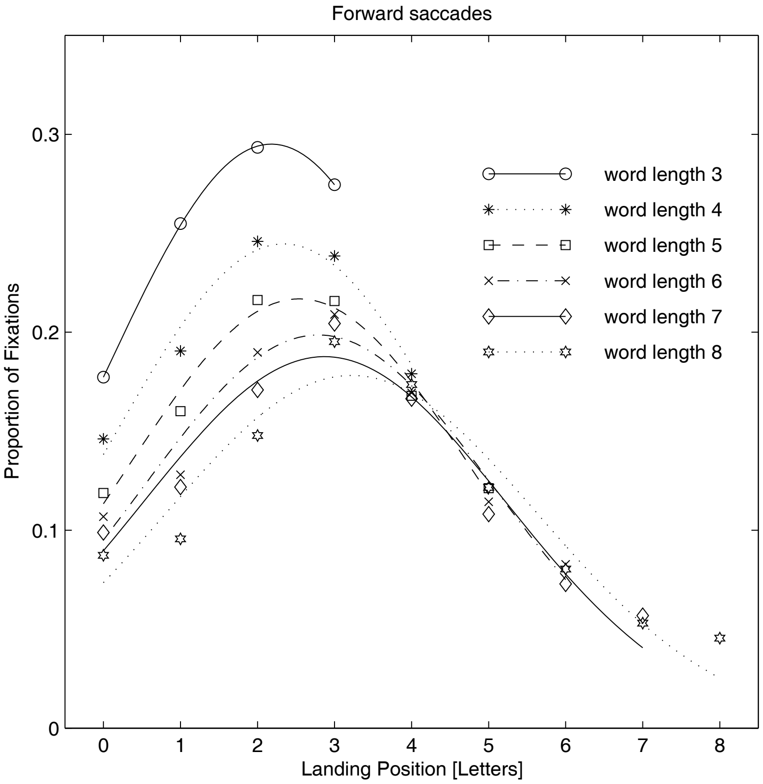

Fig. 6.1 Landing position distributions for 3- to 8-letter words. Letter 0 corresponds to the space to the left of the word. Also presented is the best-fitting normal curve for each distribution.

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[39] Initial fixations which correspond to first fixations (traditional definition, see footnote 8, p. 26) make up about 70% of all fixations.

Table 6.1 Means (M, M_C, M'), and standard deviations (*SD*) of landing position distributions for different word lengths, fitted to the normal curve; computations are based on all reading fixations except the first and last fixations in a sentence.

WORD LENGTH	CENTER OF WORD	MEAN M [LETTER POSITION]	M_C	M'	*SD*	χ^2	*N*
3	2	2.18	0.18	0.73	2.16	0	36331
4	2.5	2.34	-0.16	0.58	2.19	0.00028	24085
5	3	2.54	-0.46	0.51	2.23	0.00025	29679
6	3.5	2.79	-0.71	0.47	2.3	0.00081	25691
7	4	2.87	-1.13	0.41	2.36	0.0012	23317
8	4.5	3.22	-1.28	0.40	2.42	0.00181	18843

Note. $M_C = M$ – Center of word. $M' = M/$ word length. χ^2 denotes sum of squared residuals.

6.1.2 Estimation of the Proportion of Mislocated Fixations from Empirical Data

The composite distributions (Fig. 6.1) were used to estimate the amount of mislocated fixations in a first approximation. Specifically, it was assumed that these landing position distributions are normal distributions truncated at word boundaries. Saccades landing in the tails represent cases in which the eyes undershoot or overshoot their intended target words, leading to mislocated fixations (McConkie *et al.*, 1988).[40] Thus, words are also fixated, refixated and/or skipped due to oculomotor error. Important cases of mislocated fixations (Fig. 6.2) result from undershoot (i.e., failed skipping, unintended forward refixation, undershot regression) and overshoot (i.e., unintended skipping, failed forward refixation, overshot regression, failed backward refixation). In case of failed skipping (I), the eyes intended to land on the second word to the right (n) of the launch word (n-2), but instead landed on the next word (n-1). In case of unintended skipping (IV), the saccade was intended to land on the next word (n) relative to the launch word (n-1), but in execution the intended target word was skipped, that is the executed saccade landed on the second word to the right (n+1) of the launch word. A forward refixation can be considered as being unintended (case II) if the eyes actually planned to leave the launch word (n-1) and move to the next word (n) but instead remained on the launch word. A forward refixation failed (case V) if the eye did

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[40] McConkie *et al.* (1988) primarily discussed undershoots and overshoots of the center of words, i.e. within the word boundaries. However, oculomotor errors – when large enough – also produce under- or overshoots between words. In the current paper, we restrict our definition of mislocated fixations to this second type of error.

not – as intended – land on the launch word (*n*), but on the word to the right of the launch word (*n*+1). Likewise, a backward refixation failed (case VII) if the eye did not land on the launch word (*n*), but on the word to the left of the launch word (*n*-1). As for second-pass reading, there are undershot regressions where the eyes fell short of the intended target word (case III), as well as overshot regressions (case VI).

If, in principle, saccades are aimed at word centers, mislocated fixations will occur primarily at the beginning and end of words.

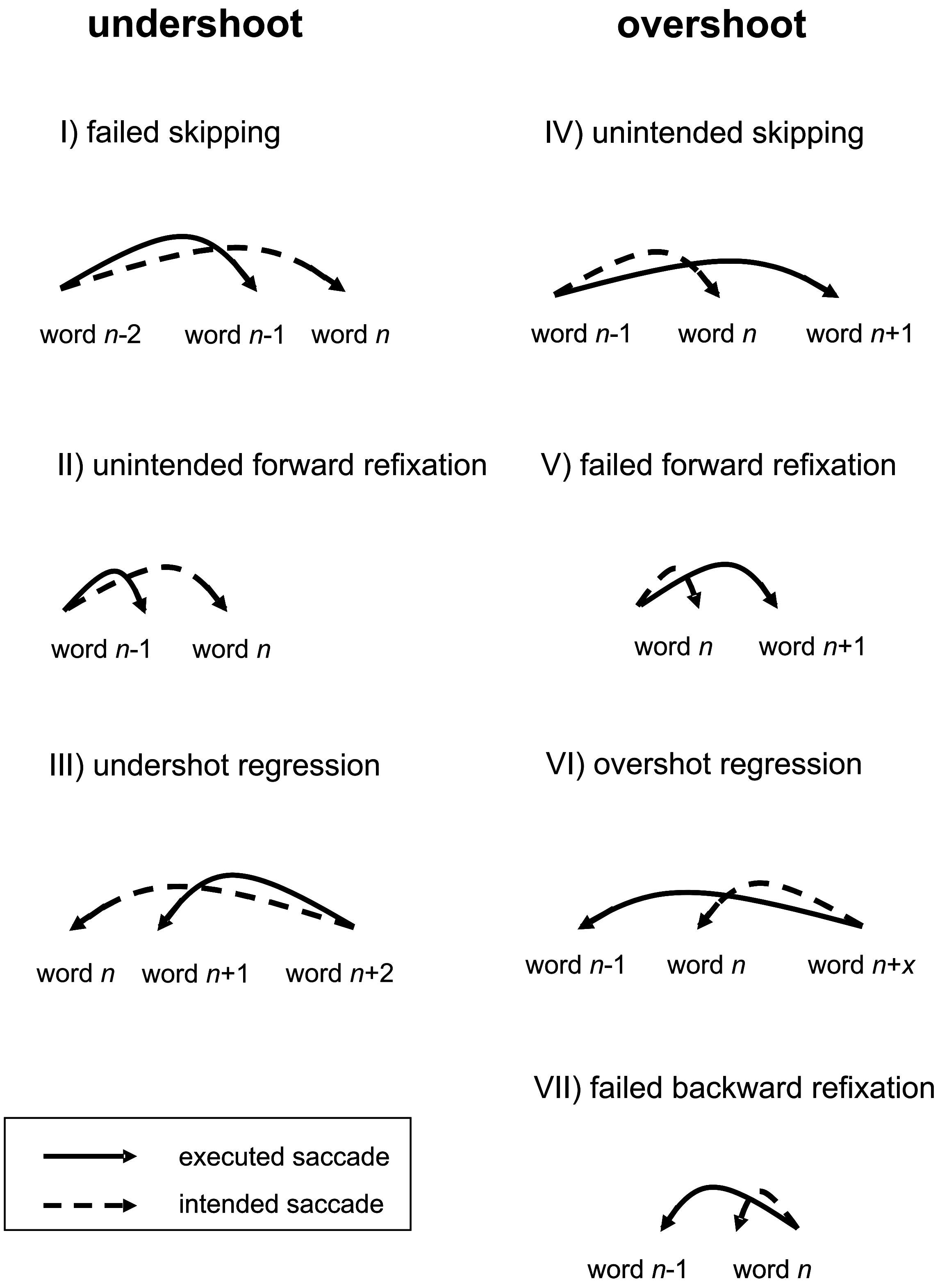

Fig. 6.2 Most important cases of mislocated fixations. According to the nomenclature used in the figure, word *n* is the intended target word. Dashed lines indicate the intended saccades which are misguided due to saccadic error; solid lines represent executed saccades.

The most severe problem for the estimation of the fraction of mislocated fixations arises from the fact that we do not know the intended target word of a saccade; we can only observe the *realized* but not the *intended* saccade size. Nevertheless, we can estimate the probability of mislocated fixations per word length category from an extrapolation of the landing position distributions to neighboring words based on certain smoothness assumptions for landing position distributions (see Fig. 4.1).

First, the experimentally observed landing position distribution can be described mathematically by the conditional probability $p_L(x|n)$ that a saccade lands on a specific letter position x of word n with length L *given* that word n was the intended word, assuming again a Gaussian probability density for landing positions. This probability density is scaled in such a way that the integral of $p(x|n)$ from 0 to L is one, since within-word landing position is limited by word boundaries, i.e.

$$p_L(x\,|\,n) = \frac{N(\mu_L,\sigma_L;x)}{\sum_{x=0}^{L} N(\mu_L,\sigma_L;x)}, \tag{4}$$

where $N(\mu,\sigma;x)$ is the normal distribution with mean μ and standard deviation σ for the stochastic variable x. To obtain estimates for the mean μ_L and standard deviation σ_L for the landing position distribution of words of length L, a grid search method (in steps of 0.1) with a minimum-χ^2 criterion was applied. Best-fitting lines for word lengths from 3 to 8 are shown in Fig. 4.1; fit parameters are listed in Table 4.1.

The thin solid line in Fig. 6.3 depicts the best-fitting normal distribution for 5-letter words, showing a mean of 2.5 letters and a standard deviation of 2.2 letters. The scaling, see Eq. (4), was done to minimize the deviation between empirical and fitted data points. Note that a scaled default normal fit[41] would overestimate the maximum and underestimate the standard deviation of the fitted normal distribution considerably (thin dashed line in Fig. 6.3). This demonstrates the advantage of the conditional probability density, Eq. (4), with parameters determined with the grid search method.

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[41] The MATLAB function ‘normfit’ was used. Mean and standard deviation of the normal distribution are computed by using the Minimum Variance Unbiased Estimator.

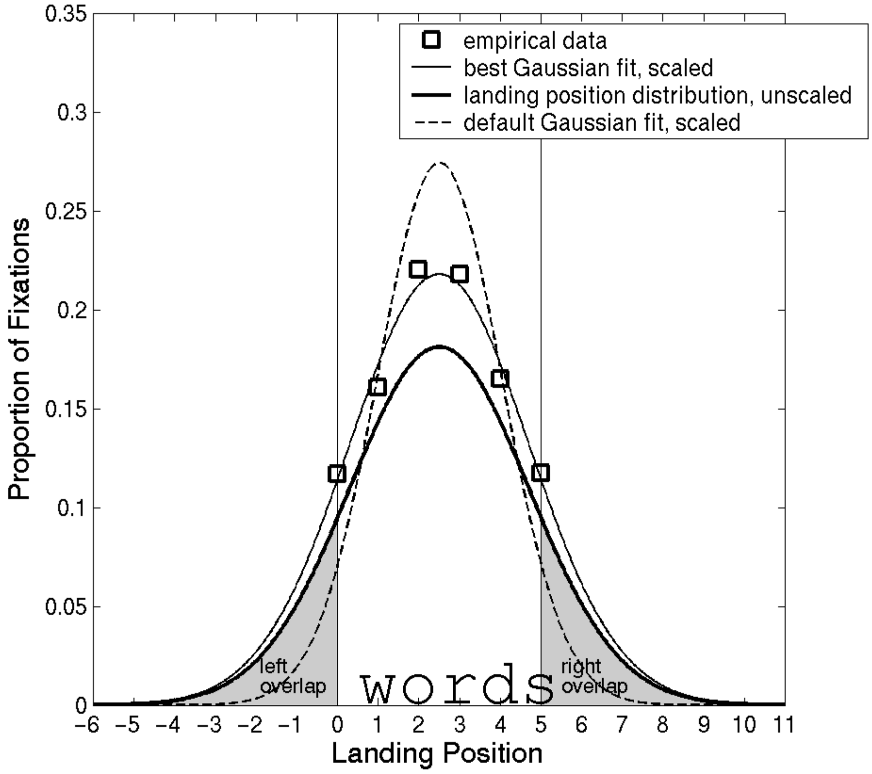

Fig. 6.3 Estimation of the proportion of mislocated fixations for words of a given length, illustrated for 5-letter words. Note that empirical data and scaled best-fitting normal curve are taken from Figure 5. Within the word boundaries, i.e. from landing position 0 to 5, the values of the scaled curve add up to 1. Left and right overlap refer to the unscaled best-fitting normal curve with the area under the total curve being 1. Proportion of mislocated fixations is the sum of left and right overlap (cf., Table 6.2).

Second, it was assumed – in the sense of a first-order approximation – that empirical landing position distributions consist of well-located fixations only. For an estimate of the proportion of mislocated fixations, the Gaussian distribution $N(\mu_L,\sigma_L;x)$ with mean μ_L and standard deviation σ_L was extrapolated beyond the word borders (bold line in Fig. 6.3). An unscaled normal distribution was used for the extrapolation because the landing position probability density is unconditioned in this case. Then, the total overlap on the left side was determined by adding up the values of the normal distribution for landing positions -6 to -1 (values for distances smaller than -6 are approximately zero and can be neglected). The overlap on the right side was determined by adding up the values of the normal distribution for landing positions 6 to 11 (again, values for distances greater than 11 can be neglected). Finally, the sum of left and right overlap represents the probability that a word of length *L generates* a mislocated fixation onto one of its neighboring words (Table 6.2). The results of these calculations suggested that the estimated proportion of mislocated fixations decreases with word length. Furthermore, for short words the right overlap representing mislocated fixations due to an overshoot was more pronounced than the left overlap. The opposite was true for long words. For them, the left overlap representing mislocated fixations due to an undershoot was more pronounced than the right overlap. These qualitative observations served as an initial plausibility check for the computations.

Table 6.2 Probabilities for generating a mislocated fixation and receiving a mislocated fixation as a function of word length. Estimations from empirical data.

WORD LENGTH	**GENERATING MISLOCATED FIXATIONS**			**RECEIVING MISLOCATED FIXATIONS**
	LEFT OVERLAP	**RIGHT OVERLAP**	**SUM**	
3	0.108	0.276	0.383	0.114
4	0.100	0.157	0.256	0.120
5	0.084	0.084	0.169	0.116
6	0.074	0.052	0.127	0.122
7	0.077	0.027	0.104	0.138
8	0.060	0.013	0.073	0.098

Finally, the probability $p_L^{mis}(x)$ that a given word n of length L *receives* a mislocated fixation at letter position x was estimated. For example, as illustrated in Fig. 6.4a, the 5-letter word “neuen” [new] was the potential recipient of a misguided saccade that was intended to land on “seinem” [his] or “Sekretär” [secretary]. Thus, there are two additive contributions: (1) The overlap to the right from word n-1 due to overshoot, $p_{n-1}^{+}(x)$, and (2) the overlap to the left from word n+1 due to undershoot, $p_{n+1}^{-}(x)$. These probabilities can be computed from the tails of word-length dependent landing-position distributions (Fig. 6.1, Table 4.1)[42],

$$\begin{aligned} p_{n-1}^{+}(x) &= N(\mu_{n-1}, \sigma_{n-1}; x + L_{n-1}) \\ p_{n+1}^{-}(x) &= N(\mu_{n+1}, \sigma_{n+1}; -x) \end{aligned} , \qquad (5)$$

where μ_{n-1} and σ_{n-1} are mean and standard deviation of the landing position distribution for words with the length $L=L_{n-1}$ determined from fitting the conditional probability

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[42] It was also attempted to compute word-based landing position distributions, i.e. for every word of the corpus. However, especially for shorter words these distributions were relatively unstable (note that a maximum of 200 subjects could contribute to such a distribution). Therefore, we decided to use the Gaussian fitted landing position distributions per word length category.

$p_L(x|n)$ in Eq. (4). The range of x has to be transformed to the coordinates of word n, i.e. $x'=x+L_{n-1}$ for the overshoot case and $x'=-x$ for the undershoot case. These two contributions are added, which gives the probability for mislocated fixations on word n,

$$q_n^{mis}(x) = p_{n-1}^{+}(x) + p_{n+1}^{-}(x) . \tag{6}$$

Finally, this probability was averaged over all words of a given length L. The result was divided by the landing position distribution for words of length L, which yielded the relation

$$p_L^{mis}(x) = \frac{\left\langle q_n^{mis}(x) \right\rangle_L}{p_L(x)} , \tag{7}$$

where $\langle . \rangle_L$ denotes the average over all words n with length L and $p_L(x)=N(\mu_L,\sigma_L;x)$ is the landing position distribution for words of length L.

Since the contributions to mislocated fixations from the left and right neighboring words depend on the word length of corresponding words, Eq. (5), the overlap was computed word by word on the basis of word triplets; for an illustration see Fig. 6.4a. The center word of the triplet ‘seinem neuen Sekretär’ [his new secretary] is the word ‘neuen’ [new]. For the center word of every triplet, the overlap was computed from the left and right word respectively. Our analysis is based on distributions for words with lengths ranging from 3 to 8. Consequently, triplets where all three words had at least three and not more than eight letters were considered. As a consequence, only 470 out of 850 possible triplets contributed to the estimation. The procedure resulted in mean proportions of mislocated fixations as a function of word length and landing position. The curve with squares in Fig. 6.4b displays the results for 5-letter words. The sum of the position-dependent values represents the overall probability of receiving a mislocated fixation as a function of word length (Table 6.2). Note that these probabilities do not depend on the length of the current word but on the lengths of the words to the left and to the right and thus on the corpus material. Finally, given the amount of mislocated fixation from overlap, $\left\langle q_n^{mis}(x) \right\rangle_L$, the *proportion* of mislocated fixations, $p_L^{mis}(x)$, relative to the Gaussian landing position distributions, $p_L(x)$, was computed according to Eq. (7), see Fig. 6.4b for an example.

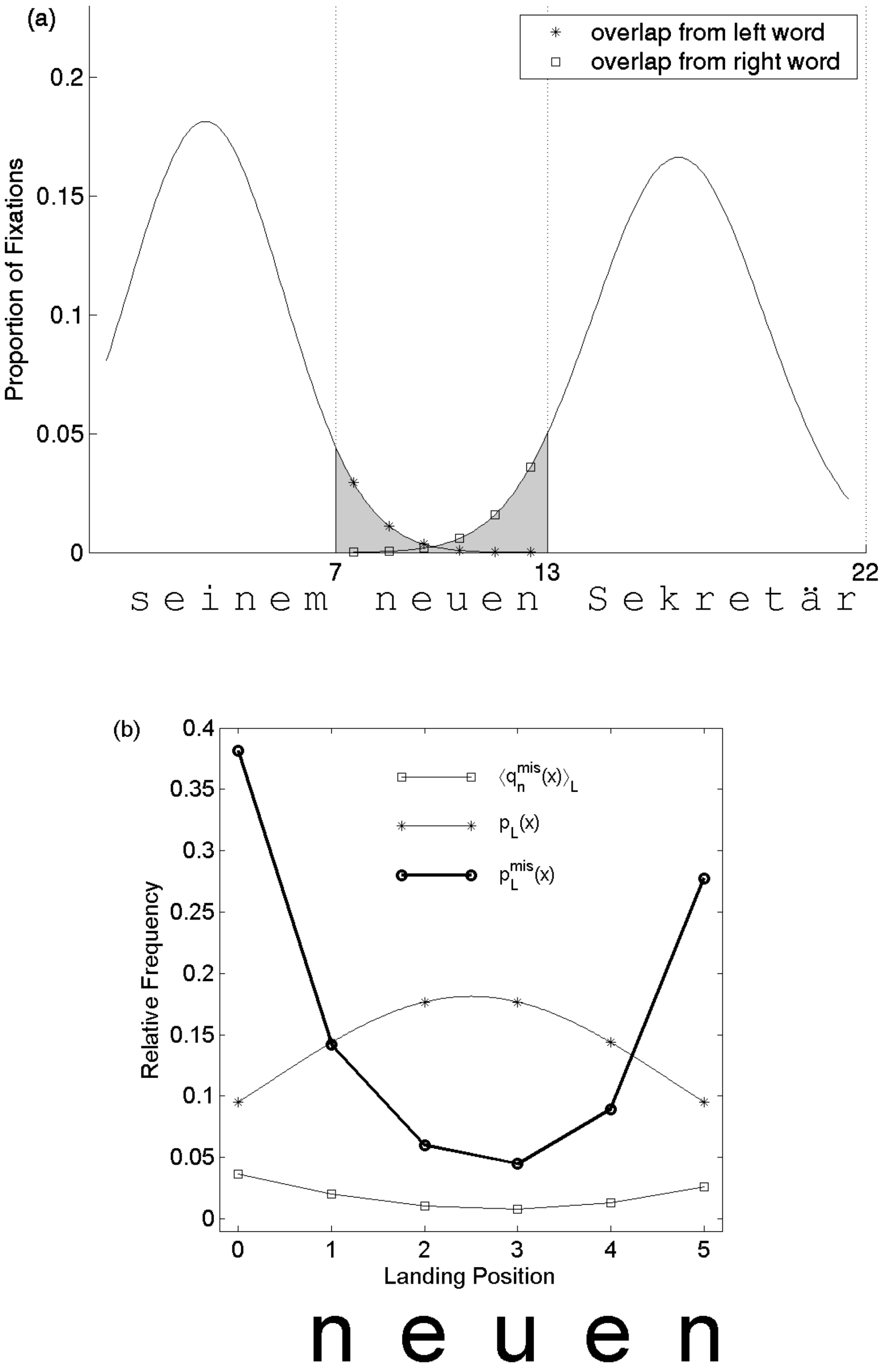

Fig. 6.4 Estimation of the proportion of mislocated fixations as a function of both word length and landing position. (a) Procedure illustrated with an example triplet. (b) Results for 5-letter words. $p_L^{mis}(x)$ denotes the relative proportion of mislocated fixations, according to Eq. (7) derived from $\left\langle q_n^{mis}(x)\right\rangle_L$ as the proportion of mislocated fixations according to the triplet algorithm and $p_L(x)$, the unscaled landing position distribution.

Applying this procedure to words of length 3 to 8 yielded probabilities for mislocated fixations as a function of word length and landing position (Fig. 6.5a). For different word lengths, the probability of being a mislocated fixation increased as the distance of the fixation location from the center of the word increased. For fixations at word center, the probability of being a mislocated fixation was very low, in particular for long words. With increasing word length, the rise of the branches of the distribution was more and more asymmetric with a steeper increase on the right side. Thus, based on the experimentally observed landing position distributions and the assumption that the underlying distributions are Gaussians, it was possible to estimate the probability for mislocated fixations as a function of word length and within-word fixation position.

6.1.3 The IOVP Effect as the Result of Error-Correction of Mislocated Fixations

With the results of the previous section, we established a qualitative explanation of the IOVP effect by error-correction of mislocated fixations. In this section, some calculations are added to check the proposed model quantitatively. It was assumed that the oculomotor system is able to recognize whether the eye landed on the intended target word or not. It is commonly accepted that saccade amplitudes are determined by population-coded activations in the superior colliculus (e.g., Sparks, 2002, for a recent review). Accordingly, saccades are controlled by an efference copy of the motor signal to the eye muscles (Wurtz, 1996; Carpenter, 2000; see also Bergeron, Matsuo, & Guitton, 2003). Consequently, gaze errors are continuously monitored during saccades, which potentially provides a very fast detection of saccade errors. Thus, the principle of efference copies processed in the brainstem superior colliculus suggests that a mislocated fixation can be detected immediately after the end of the misguided saccade. Therefore, a new saccade program can be started at the beginning of the mislocated fixation if the intended target word is missed. The immediate start of a new saccade program leads to decreased durations for mislocated fixations. Since mislocated fixations are more frequent at the beginning and end of words, we should find an inverted U-shaped relationship for fixation duration as a function of landing position.

As a quantitative check of this prediction, fixation duration was calculated as a function of landing position according to the mechanism of error-correction of mislocated fixations. For simplicity, it was assumed that the fixation durations F_L for words of length L are independent of landing position without error-correction. The resulting corrected fixation duration is given by

$$F_L^C(x) = F_L(1 - p_L^{mis}(x)) + \tau_C p_L^{mis}(x), \tag{8}$$

where $p_L^{mis}(x)$ is the probability for mislocated fixations on a word of length L at letter position x and τ_C denotes the latency of the error-correcting saccade program. For the calculation presented in Fig. 6.5c, a value of τ_C=125 ms was used.[43] The unknown value of F_L was chosen in such a way that the resulting mean value for $F_L^C(x)$, averaged over all landing positions, equaled the experimentally observed mean fixation duration for a word of length L.

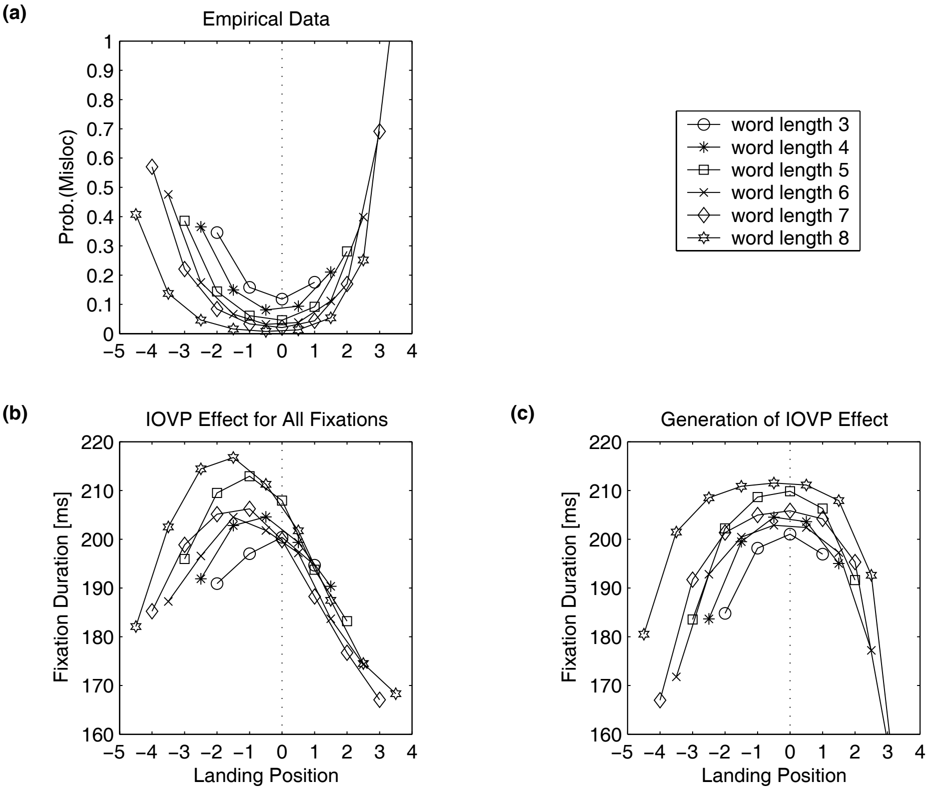

Fig. 6.5 Error correction of mislocated fixations as an explanation for the IOVP effect. (a) Proportion of mislocated fixations as a function of word length and landing position. (b) Empirical IOVP effect: The inverted U-shaped curves represent the mean fixation duration (for all fixations except first and last fixations in a sentence) as a function of word length and landing position. (c) Generation of the Fixation-Duration IOVP effect.

While results were in good agreement with experimental data, the model did not perfectly reproduce all aspects of empirical IOVP curves. For example, the empirical IOVP effect (Fig. 6.5b) was stronger for fixations at the end of words; fixations on the

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[43] This value is lower than the 150 ms reported by Rayner *et al.* (1983) as the average minimum saccade latency. We set the value for τ_C to 125 ms because latencies for corrective saccades are assumed to be even shorter, with a mean closer to 100 ms (cf., O'Regan & Lévy-Schoen, 1987). However, the convex shape of the generated IOVP effect did not depend on the parametric variation of τ_C within 100-175 ms.

right branch of the IOVP curve were shorter than those on the left branch. The reproduction of this asymmetry required that the right branch of the mislocated fixations rises more steeply than the left branch (Fig. 6.5a). This asymmetry of the IOVP effect could be reproduced for 7- and 8-letter words only. Furthermore, for most word lengths the maximum of the empirical IOVP curves was slightly left of word center whereas the curves generated with the model peaked at the center of words. Despite these differences, the error correction associated with mislocated fixations could serve as a quantitatively plausible explanation of the IOVP effect.

6.2 Applying the Algorithm to *Z* String "Reading" Data as an Oculomotor Control Condition

In the previous section the Fixation-Duration IOVP effect was explained to be a low-level oculomotor phenomenon. The fact that the Fixation-Duration IOVP effect also exists in the *z* string "reading" oculomotor control condition (see Fig. 5.7, p. 133), and thus in the absence of word identification demands, lends strong support to this notion. To further test the validity of the introduced IOVP generating algorithm, it was examined whether the algorithm is able to generate the very strong IOVP effect that was observed in the *z* string "reading" condition. First, landing position distributions are very similar for mindless reading (Fig. 6.6a) as compared to normal reading (Fig. 6.6b). Consequently, the estimated proportions of mislocated fixations are also similar (Fig. 6.6, panel c and d).

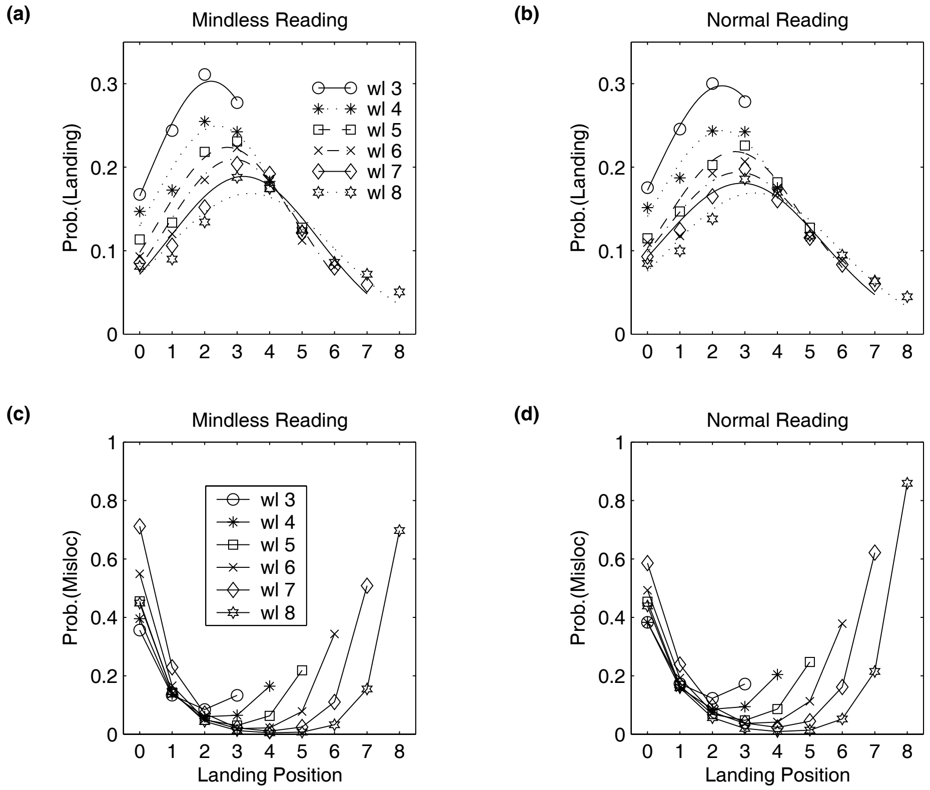

Fig. 6.6 Landing position distributions for *z* string “reading” data (a) vs. normal reading data (b). Based on these distributions, the proportion of mislocated fixations as a function of word length and landing position was computed, again for *z* string “reading” data (c) vs. normal reading data (d).

The empirical IOVP effect for mindless reading data is qualitatively reproduced by the algorithm (Fig. 6.7b). Thus, the introduced IOVP generating algorithm is able to generate the strong Fixation-Duration IOVP effect obtained in the mindless reading condition.

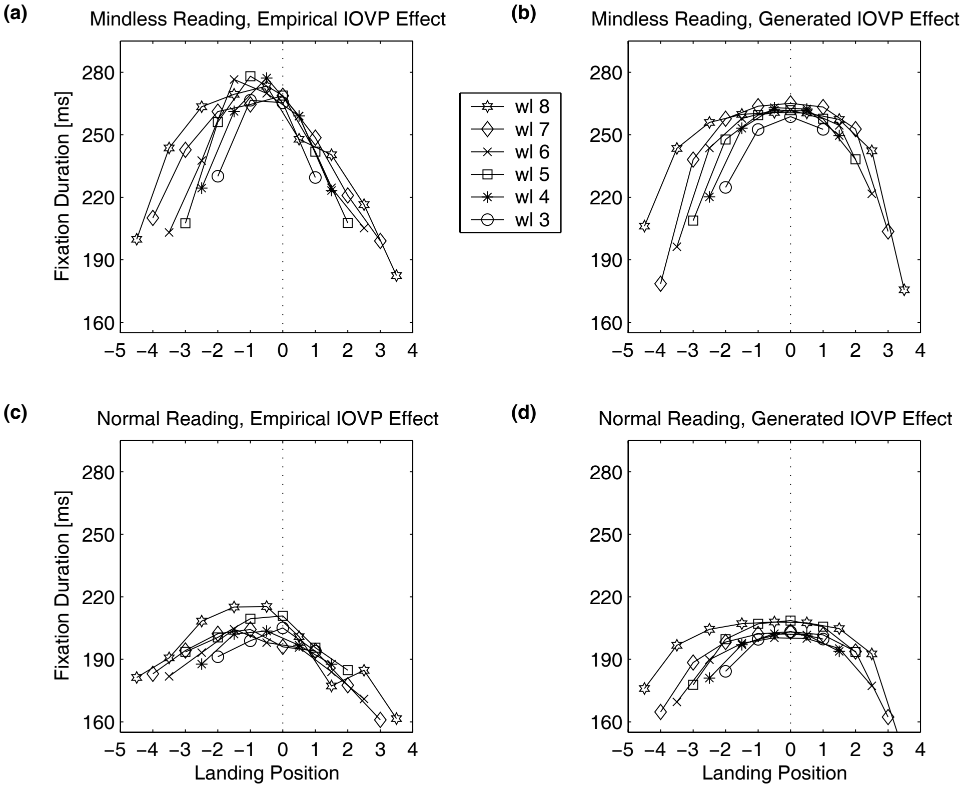

Fig. 6.7 Comparison of the empirical Fixation-Duration IOVP effect (left panels) with the IOVP effect generated by the algorithm introduced in Sec. 6.1 (right panels), for *z* string “reading” data (a, b) vs. normal reading data (c, d).

At first glance, this seems to be counterintuitive because landing position distributions and thus the probability of mislocated fixation are very similar in normal and mindless reading. Recall that the IOVP effect was reproduced according to Eq. (8). There, F_L represents the mean fixation duration for a word and/ or string of length *L*. Thus, F_L reflects the empirical fixation durations which are considerably higher in the mindless reading compared to the normal reading condition. For generating the data presented in Fig. 6.7b and Fig. 6.7d, the saccade latency in response to a mislocated fixation, τ_C, was set to 125 ms (as in Fig. 6.5c). Consequently, for the mindless reading data, F_L is much higher than τ_C. With other words, the difference between F_L and τ_C is much higher in the mindless than in the normal reading condition. This is why the introduced IOVP generating algorithm indeed reproduces the strong Fixation-Duration IOVP effect obtained in the mindless reading condition.

6.3 Simulations with the SWIFT Model

Simulations with the SWIFT model (Engbert *et al.*, 2005) were essential for developing the IOVP model described in Sec. 6.1. Therefore, results from simulations with the SWIFT model are presented in the current section. First, the algorithm developed to estimate the proportion of mislocated fixations from empirical data (see Sec. 6.1.2, pp. 143) was validated with numerical simulations using the SWIFT model (Sec. 6.3.1). Second, the magnitude of different cases of mislocated fixations as well as responses to mislocated fixations were explored with SWIFT simulations (Sec. 6.3.2). Third, it will be outlined briefly how the ideas concerning the IOVP effect, as developed here, were implemented in the SWIFT model (Sec. 6.3.3). When introducing the IOVP model, it was suggested that the oculomotor system responds to a mislocated fixation with the immediate start of a new saccade program (see Sec. 6.1.3, pp. 151). In Sec. 6.3.4 it will be shown how this new theoretical claim relates to assumptions on saccade programming in the SWIFT model. Importantly, it will be elucidated that the proposed mechanism does not require a reduced programming time for saccades following mislocated fixations. Rather, the decreased duration for mislocated fixations results from the fact that the majority of saccades following mislocated fixations are initiated at the beginning of the mislocated fixation.

6.3.1 Testing the Estimation Algorithm for Mislocated Fixations with SWIFT Simulations

The algorithm for reconstructing the proportion of mislocated fixations (as a function of within-word landing position) from empirical data was validated by numerical simulations with the SWIFT model (Fig. 6.8; see also Engbert *et al.*, 2005). This is a very strong test of the algorithm because model simulations allow a “double check”. On the one hand, we can apply the algorithm developed in Sec. 6.1.2 (pp. 143) to simulated data (Fig. 6.8, symbols connected with straight lines). On the other hand, the transparency of a computational model enables us to extract the exact proportion of mislocated fixations by comparing intended and realized saccade targets (Fig. 6.8, symbols connected with dotted lines).

Recall that the estimated mislocated fixation probability curves were computed from extrapolations of landing position distributions. The SWIFT model is able to reproduce the characteristics of landing position distributions (Engbert *et al.*, 2005, Fig.

16a). Consequently, the model provides estimated mislocated fixation probability curves that are in quite a good agreement with the curves estimated from the empirical data (compare Fig. 6.8, straight lines, with Fig. 6.5a). Most importantly, the mislocated fixation probability curves that were estimated from simulated data are also in good agreement with the exact results (Fig. 6.8). These results prove that the estimation algorithm is able to reconstruct the exact results from model simulations.

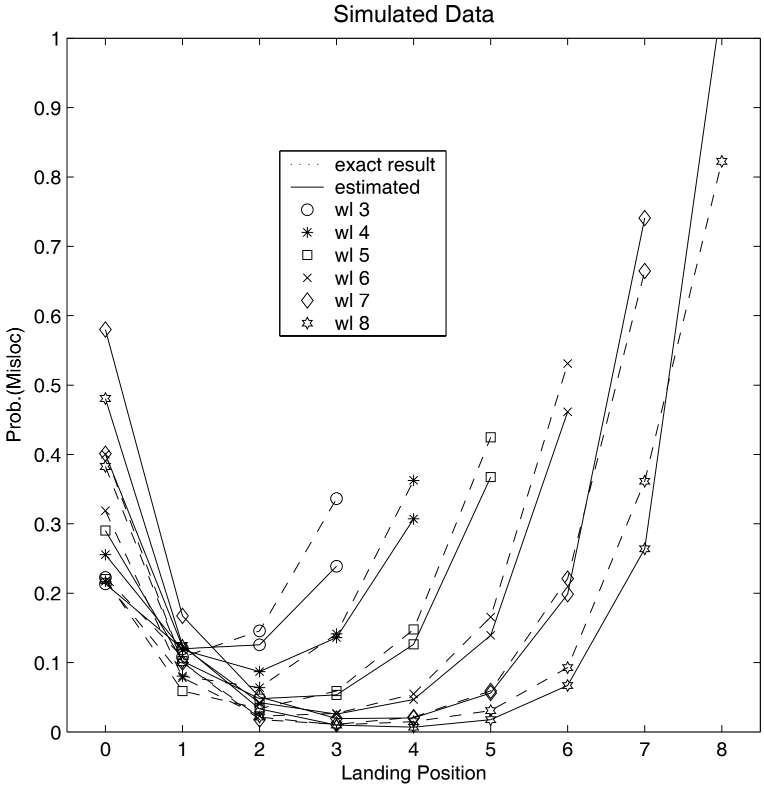

Fig. 6.8 Testing the estimation algorithm for mislocated fixations with SWIFT simulations. Proportion of mislocated fixations as a function of landing position: Estimated curves are calculated from overlapping landing position distributions; exact results are directly computed from model simulations.

6.3.2 Exploring Mislocated Fixations

6.3.2.1 Magnitude of different cases of mislocated fixations

Another advantage of numerical simulations with a computational model is that the prevalence of different types of mislocated fixations (cf., Fig. 6.2, p. 145) can be investigated in detail. After removing the first and last fixation in a sentence it turned out that 23.23% of all fixations generated by the model (200 realizations with the SWIFT model) were mislocated. Table 6.3 provides a complete synopsis of all mislocated fixation cases.

Table 6.3 Simulations with the SWIFT model. Prevalence of mislocated fixation cases. Proportions are provided relative to all mislocated fixations (column 2) and/or relative to all fixations (column 3), respectively.

UNDERSHOOT	**X/MISLOC**	**X/ALL**
failed one-word skipping (case Ia)	22.68%	5.27%
other types of failed skipping (case Ib)	19.11%	4.44%
unintended forward refixation (case II)	14.39%	3.34%
undershot regression (case III)	12.77%	2.97%
Σ UNDERSHOOT	68.94%	16.02%
OVERSHOOT		
unintended skipping (case IV)	9.89%	2.30%
failed forward refixation (case V)	18.40%	4.28%
overshot regression (case VI)	2.10%	0.49%
failed backward refixation (case VII)	0.68%	0.16%
Σ OVERSHOOT	31.07%	7.22%
Σ ALL	100%	23.24%

Mislocated fixations can be distinguished as being caused by an undershoot vs. overshoot of the intended target word. The undershoot cases comprise failed skipping, unintended forward refixation, and undershot regression (Fig. 6.2, p. 145). For example, a forward refixation is unintended (case II) if the eyes actually planned to leave the launch word (*n*-1) and move to the next word (*n*) but instead remained on the launch word. Undershoot cases cover 69% of all mislocated fixations. Note that failed skipping (case I, 41.79%) is the by far most frequent case of mislocated fixations. 3.34% of all fixations are unintended forward refixations (case II). Somewhat surprisingly, the SWIFT model also produces a certain amount of undershot regressions (case III, 2.97% of all fixations). This effect is related to the fact that a saccade range error applies also to inter-word regressions in SWIFT (cf., Sec. 7.3.2, pp. 192). It is reasonable to expect, however, that this behavior of the model can be optimized by changing the oculomotor parameters for regressions.

The overshoot cases consist of unintended skipping, failed forward refixation, failed backward refixation, and overshot regression (Fig. 6.2, p. 145). Overshot inter-word regressions (case VI) as well as failed backward refixations (case VII) hardly ever occur. However, 4.28% of all fixations are failed forward refixations (case V) while 2.3% of all fixations are unintended skippings (case IV).

Further analyses of two-fixation cases suggested that failed forward refixations are mostly associated with shorter words while the landing positions are close to word beginnings (Fig. 6.9b). Unintended forward refixations were found to occur mostly on longer words, with landing positions close to the end of the refixated word (Fig. 6.9a).

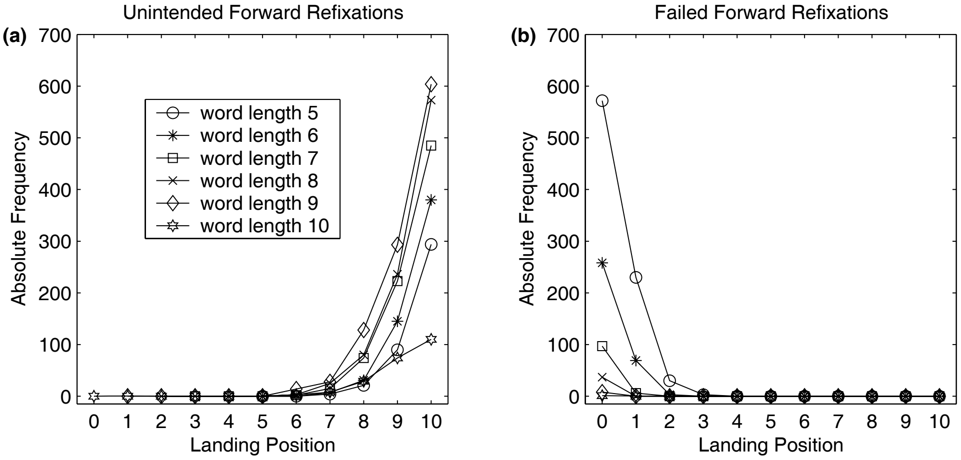

Fig. 6.9 Simulations with the SWIFT model. Examination of two-fixation cases. Landing position distributions for (a) unintended forward refixations, and (b) failed forward refixations as a function of word length. In panel (a), data presentation is aligned to the last letter of the word with the maximum word length analyzed.

6.3.2.2 Responses to mislocated fixations

The exploration of mislocated fixations raises the interesting question how the eye-movement control system *responds* to a mislocated fixation. This is obviously another problem which can only be studied with the help of model simulations.

To establish a reference for what follows, we will first consider the model's response to well-located initial fixations (Fig. 6.10). Every word length category is represented with a double panel. The respective upper panel displays the corresponding *landing position distribution* while the lower panel shows *responses* to this well-located initial fixation as a function of landing position.

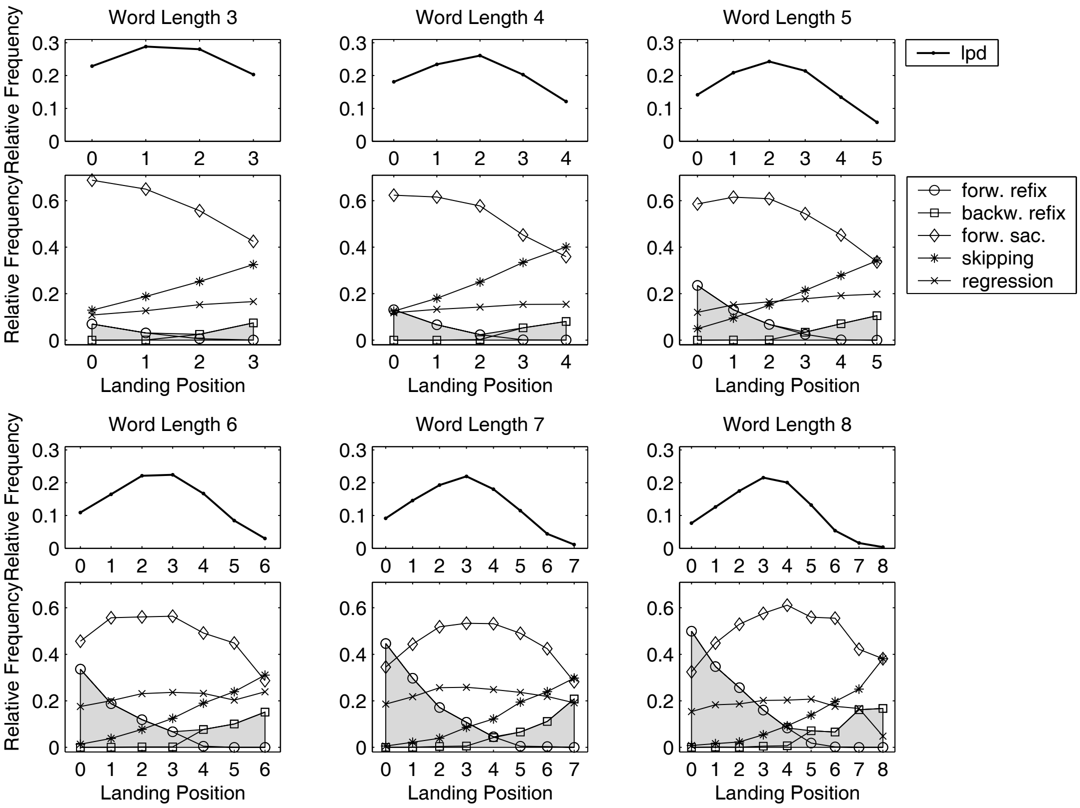

Fig. 6.10 Simulations with the SWIFT model. Response to well-located initial fixations. Every word length category is represented with a double panel. Upper panels display landing position distributions while lower panels show the proportion of different saccade types with which the eyes move on after initially fixating on a word.

The landing position distribution panels show that the SWIFT model nicely replicates the preferred viewing location phenomenon. As for the response panels it is important to note that, for a given landing position, the displayed data points sum up to 1. For any word length and any landing position, an inter-word forward saccade is the most frequent response after initially landing within a word. For longer words, the position-dependent curve develops an inverted U-shape. Thus, towards either end of the word, the frequency of responding with an inter-word forward saccade decreases, as compared to the center of the word. This behavior is clearly compensated by the U-shaped refixation curve which originates when forward refixations (line with circles) and backward refixations (line with squares) are jointly considered as is emphasized with the gray-shaded area under the curve. In addition, the proportion of skipping responses strongly increases with increasing initial landing position (*-line). Interestingly, the inter-word regression response (*x*-line) appears not to be modulated by initial landing position.

How does this picture change when mislocated fixations are considered? Failed skipping is the most frequently occurring type of mislocated fixations (Table 6.3). In this case, the eyes undershot their intended target word. It is predicted that these undershoot saccades predominantly land at the *end* of *the* word (in case of an intended *one*-word skip) or *a* word (in case of an intended *multiple*-word skip) to the left of the intended target word.[44] Indeed, landing position distributions for failed skipping saccades are clearly shifted to the right, having their maximum at the last letter of the word (Fig. 6.11). Thus, these saccades predominantly land at the end of words.

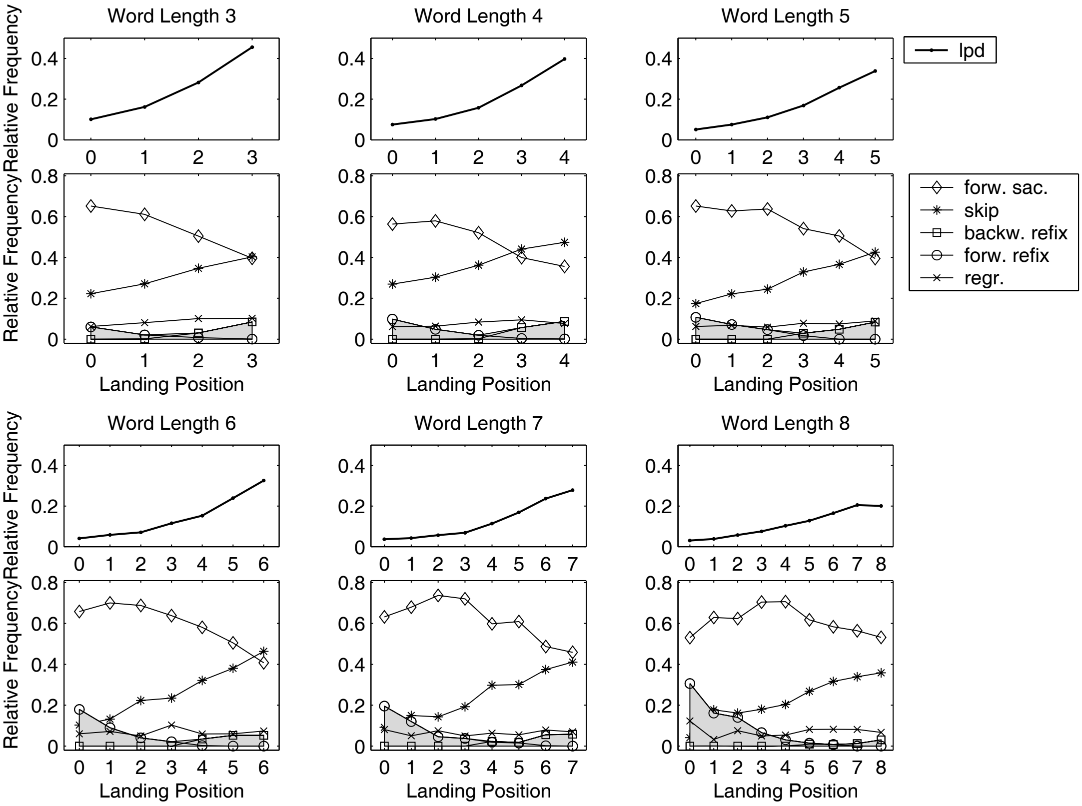

Fig. 6.11 Simulations with the SWIFT model. Response to failed skipping as the most frequently occurring case of mislocated fixations. Upper panels display landing position distributions while lower panels show the proportion of different saccade types with which the eyes move on.

Two responses apparently play a major role when failed skipping occurs (Fig. 6.11, response panels): The SWIFT model primarily responds with a skipping of the next word(s) or simply a forward saccade to the next word. Refixations and regressions

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[44] Please note that this prediction does not imply that most fixations landing at the end of a word are mislocated in the sense that the undershot the intended target word. Rather, fixations at the end of words also comprise saccades that did land on the selected target word but overshot the center of this word.

seem to play a minor role.[45] For illustration, lets consider the case of a failed one-word skipping. If the misguided saccade is followed by a saccade to the next word (one-word forward saccade), the error of initially not hitting this word is corrected. However, it is possible that this particular word was fully processed from the parafovea during the mislocated fixation. In this case, a corrective saccade to this word is no longer necessary. Instead, the eyes proceed with skipping the word.

6.3.3 The Fixation-Duration IOVP Effect in the SWIFT Model

Simulations with the SWIFT model (Engbert *et al.*, 2005) were essential for developing the IOVP model described above. Therefore, it is now briefly touched upon how the Fixation-Duration IOVP effect is generated within the framework of the SWIFT model.

Theoretically, all types of fixations can be mislocated. The explanation of the IOVP effect, as suggested in Sec. 6.1 above, is based on the assumption that mislocated fixations (often) trigger a new saccade program immediately. Thus, we predict and observe an IOVP effect for durations of single fixations, first of multiple fixations, and second of multiple fixations (Sec. 5.1, pp. 124; see also Vitu *et al.*, 2001). The empirical estimates, however, were based on *all* fixations. Consequently, the suggested IOVP mechanism is not able to differentiate between different types of fixations (e.g., single, first, second).

Again, simulations with the SWIFT model were employed to investigate and reproduce quantitative differences between various IOVP functions. The correction mechanism for mislocated fixations, implemented as Principle VI, was able to reproduce the IOVP effect for single fixation durations (Engbert *et al.*, 2005, Fig. 15). However, to reproduce the IOVP effect for the first of multiple fixations as well as the fixation duration trade-off effect for two-fixation cases (Fig. 5.5, p. 129), the model had to be furnished with Principle VII: It is assumed that saccade latency is modulated by the amplitude of the intended saccade (see Engbert *et al.*, 2005, Appendix B with an incremental model comparison). The joint implementation of both principles is able to reproduce the IOVP effect for all fixations (Fig. 6.12).

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[45] Note that results for responses to landing positions at word *beginnings* are not very sound since these landing positions are infrequent.

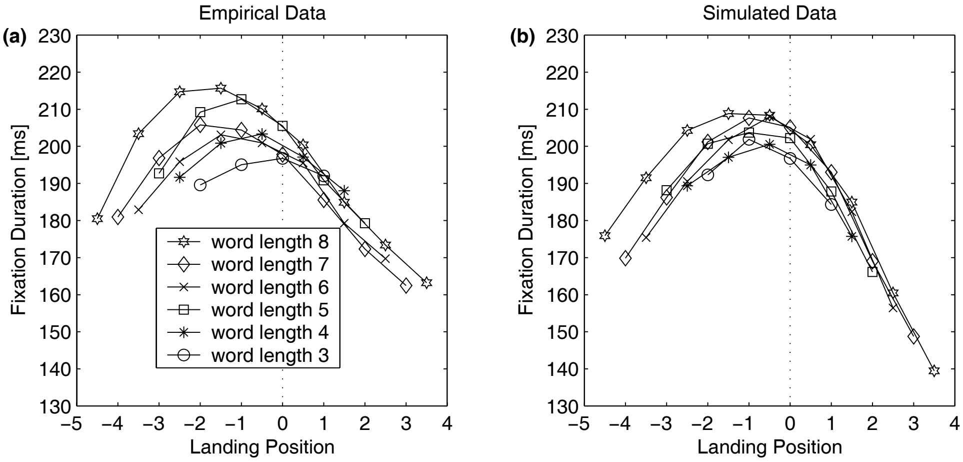

Fig. 6.12 Mean fixation duration as a function of word length and landing position within a word, based on all fixations except first and last fixations in a sentence. Empirical (a) vs. simulated (b) data.

6.3.4 About the Latency of Saccades Following Mislocated Fixations

When estabilishing a link between mislocated fixations and the Fixation-Duration IOVP effect, it was suggested that a new saccade program is started instantaneously if the eyes missed the intended word (Sec. 6.1.3, p. 151). Consequently, in this special situation the next saccade is programmed right at the beginning of the current (unfortunately mislocated) fixation. In this case, saccade latency corresponds to fixation duration.

On average, the immediate start of a saccade program will lead to decreased durations for mislocated fixations. This conjecture is valid as long as initiations of new saccade programs occur on average with a finite interval after fixation begin. Unfortunately, we do not have precise knowledge about how long it takes to program a saccade in continuous reading. Note that estimates reported in the literature (e.g., saccade programming times ranging between 180 and 250 ms) do not stem from reading experiments but are inferred from double step paradigms (e.g., Becker & Jürgens, 1979). When generating the IOVP effect based on empirical data (Sec. 6.1.3, Fig. 6.5c), the latency of the error-correcting saccade program was set to τ_C=125 ms. Note that any value smaller than the average fixation duration per word length would generate an IOVP effect; however, the smaller τ_C the stronger the generated IOVP effect.

Simulations with a computational model, however, allow to investigate the relation between saccade latency and fixation duration in much more detail. In the SWIFT model (Engbert *et al.*, 2005), the assumption of an immediate start of an error-correction saccade program is implemented as Principle VI: If there is currently no labile saccade program active, a new saccade program is immediately started. The target of this saccade will be determined at the end of the labile saccade stage according to the general rule (Principle IV). In eye-movement research in reading, fixation durations are generally interpreted in terms of latencies for subsequent saccades[46] (cf., Radach & Heller, 2000). Thus, it is assumed that the next saccade program is started close to the beginning of the current fixation. In SWIFT, however, saccade programs are generated autonomously and in parallel (see Fig. 19.2 in Kliegl & Engbert, 2003, for an illustration). This has several implications. First, different from the E-Z Reader model (Reichle *et al.*, 2003), saccades are not triggered by a cognitive event. Second, fixation durations are basically realizations of a random variable; saccade latency is randomly sampled from a gamma distribution. However, lexical activation can delay the initiation of a saccade program via the inhibition by foveal lexical activity (Principle III). Third, saccade latency is not equal to fixation duration. The program for a saccade, which terminates the current fixation, is generally initiated before or after the start of the current fixation. Now, in addition, a corrective saccade program in response to a mislocated fixation was introduced. If there is currently no labile saccade program active, a new saccade program is initiated at the beginning of the (mislocated) fixation. Thus, in case of a mislocated fixation SWIFT's autonomous saccade timer is overruled. As a consequence, the program for the saccade terminating a mislocated fixations is initiated earlier (on average) than in the case of a well-located fixation, which leads to the reduced fixation duration for mislocated fixations.

In Fig. 6.13, saccade programs that were executed and thus not cancelled later in time are considered. Computed is the time difference (in ms) between the start of such a saccade program and the start of the current fixation. When considering well-located fixations, we obtain a relatively broad distribution with most saccade programs initiated during the current fixation. However, the picture drastically changes for mislocated fixations. First, there are saccade programs that were initiated *before* the start of this mislocated fixations (ca. 15% of all cases, Fig. 6.13b), reflecting the situation that there was a labile saccade program active in the moment the eyes landed on an unintended

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[46] Saccade latency is defined as the time needed to plan and execute a saccade.

word. However, most of the time this was not the case leading to the immediate start of a new saccade program (Principle VI). Therefore, the curve presented in Fig. 6.13a has a very pronounced peak at the start of the current fixation. As simulations suggest that mislocated fixations comprise about 23% of all fixations, this peak, though attenuated, reappears when all fixations are considered.

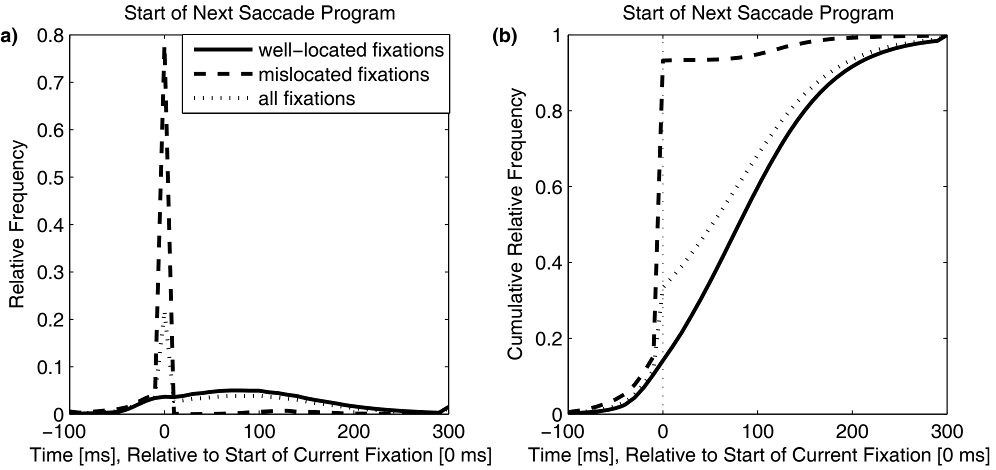

Fig. 6.13 Simulations with the SWIFT model. Start of next saccade program, relative to the start of the current fixation for well-located vs. mislocated fixations. The 0 value on the *x*-axis marks the start of the current fixation. Thus, negative values represent saccade programs that were started before the start of the current fixation. (a) Relative frequencies. (b) Cumulative relative frequencies.

It is important to note that the correction mechanism cannot increase fixation duration since the corrective saccade program is only initiated if there is currently no labile saccade program active. In addition, as long as the probability for an active saccade program at the beginning of a fixation is smaller than one (which is the case in SWIFT simulations), the mechanism can only *decrease* but not increase the mean duration of mislocated fixations (see Fig. 6.14). It shall be emphasized, however, that a shortened duration for mislocated fixations does not imply a reduced programming time for saccades following mislocated fixations; rather, as for any other saccade, saccade latency is randomly sampled from a gamma distribution (see above).

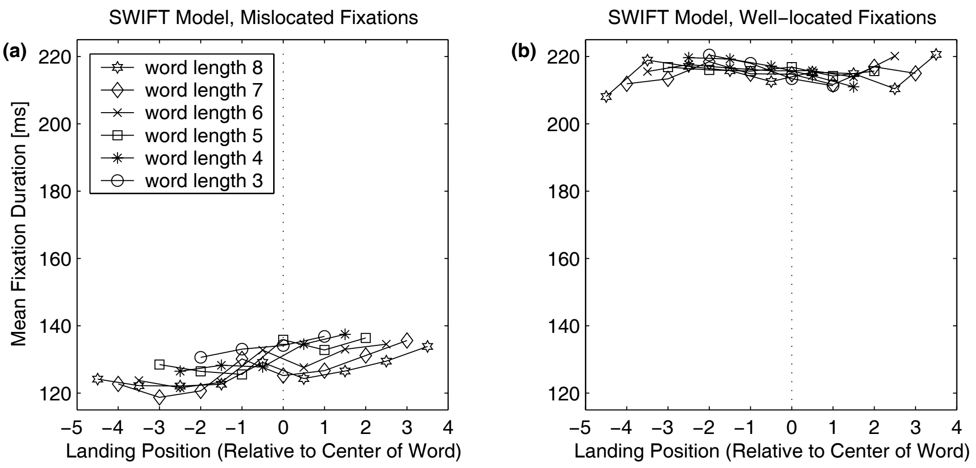

Fig. 6.14 Simulations with the SWIFT model. Mean fixation duration as a function of word length and landing position within a word, for mislocated fixations (a) vs. well-located fixations (b).

6.4 Evidence From Reading Experiment with Recurrent Sentence Shifts (Exp. 6)

In Sec. 6.1 (pp. 141) it was suggested that the Fixation-Duration IOVP effect would arise from mislocated fixations. In this regard, the reading with recurrent sentence shifts experiment (Exp. 6) was expected to be informative since sentence displacements could induce mislocated fixations. Therefore, the Fixation-Duration IOVP effect was examined for critical fixations after saccade-contingent sentence displacements (Sec. 6.4.1) as well as for fixation durations following critical saccades (Sec. 6.4.2).

6.4.1 Critical Fixations following Sentence-Shift Saccades

A closer look at the dynamics at work revealed that the experimental manipulation created a very complex situation.

“Real” mislocated fixations. A “real” mislocated fixation occurs when the eyes, due to oculomotor error, land at a different than the intended target word (see Fig. 6.2, p. 145). “Real” mislocated fixations predominantly occur at the beginning and ends of words because the eyes overshot or undershot the intended target word (see Fig. 6.5a, p. 152).

Experimentally induced mislocated fixations. Recall that 22% of all displacement saccades led to the fixation of a word other than the anticipated word. The anticipated word is the word the eyes would have landed on if there hadn’t been a sentence shift. Thus, quite frequently mislocated fixations were induced by the sentence shifts.

Experimentally induced mislocated fixations occur at word beginnings and word ends (see Fig. 4.14, p. 117).

Interactions. Because "real" mislocated fixations also predominantly occur at word edges, it is likely that there are many instances where the word denoted as the *anticipated* word is actually not the *intended target* word. Consequently, what is assumed to be an experimentally induced mislocated fixation, does not necessarily need to be a mislocated fixation. Thus, between-word landing shifts create a rather complex situation because both "induced" mislocated fixations as well as "real" mislocated fixations are involved.

Improvement of landing position situation. Furthermore, the sentence shift could actually improve (and thus not only impair) the landing position situation. On the one hand, a sentence shift could potentially correct a within-word undershoot or overshoot in that it brought the eyes (closer) to the center of the word as the OVP. On the other hand, a between-word landing shift could potentially correct what would have been a mislocated fixation. Besides, it has been argued that not every mislocated fixation needs to be corrected (cf., Sec. 6.3.2.2, pp. 159, for simulated responses to failed skipping; see also Sec. 6.5.3, pp. 174). Within-word landing shifts could influence that decision.

Modulation of critical fixation duration. The fixation following the displacement saccade was termed as critical fixation. Previous analyses showed that durations of critical fixations were influenced by shift condition (Sec. 3.4.3.1.4, pp. 90). It was argued that fixation duration is modulated by time constraints associated with the revision and/ or cancellation of a pre-planned program for the critical saccade, or the programming of the critical saccade during the critical fixation, taking the changed landing position situation into account.

Taken together, we face rather non-transparent dynamics that are hard to disentangle with analyses of empirical data. As a global analysis, Fixation-Duration curves were computed for fixations after sentence-shift saccades leading to either within-word or between-word landing shifts, according to after-shift coordinates[47] (Fig. 6.15). Data were broken down by word length, landing position, and shift condition.

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[47] Different than in the case of landing position distributions, it is less informative to consider IOVP curves according to *before*-shift coordinates because the duration of the critical fixation is reflective of the oculomotor responses to sentence displacements.

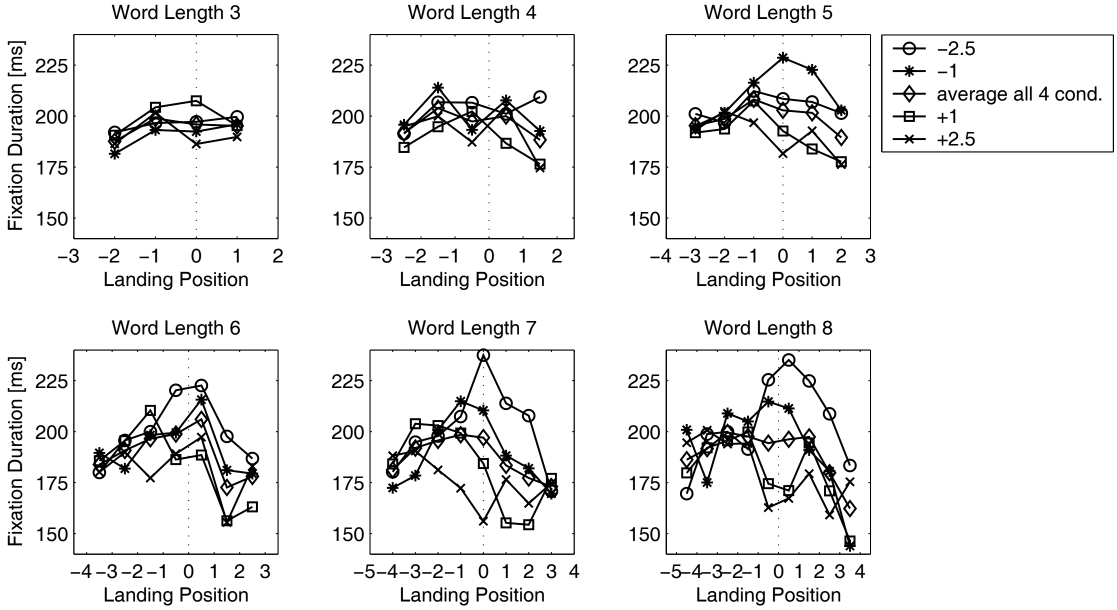

Fig. 6.15 Reading with recurrent sentence shifts experiment. Fixation-Duration IOVP effect for fixations after sentence-shift saccades. Computations are based on *after*-shift coordinates. Data are plotted as a function of word length and shift condition, with each panel representing data for a given word length (5 through 10).

For some of the tested word length × displacement conditions combinations a Fixation-Duration IOVP effect exists, for others not. Compared to data from other experiments not manipulating landing positions (Chapter 5, pp. 122), the effects are clearly attenuated and somewhat noisy. For longer words, the IOVP curves seem to somewhat reflect landing position distributions in that the IOVP curves are horizontally displaced in accordance with the displacement condition values (cf., Fig. 4.12, p. 115, for within-word landing shifts). Interestingly, when data are simply averaged across all four displacement conditions (curves with diamonds), the “normal” IOVP effect – though attenuated – emerges.

In Sec. 6.1.3 (pp. 151) it was suggested that mislocated fixations can be diagnosed by the oculomotor system and are responded to with the immediate start of a new saccade program which will, on average, lead to a decreased duration for mislocated as compared to well-located fixations. With regard to the sentence-shift experiment, mislocated fixations should be more prevalent after experimentally induced between-word landing shifts as opposed to within-word landing shifts. Consequently, fixation durations after between-word landing shifts should be shorter than fixation durations after within-word landing shifts. Empirical data from the present experiment support that prediction. On average, fixations after between-word shifts are shorter than fixations after within-word shifts (187 vs. 197 ms), a finding which is reflected in a leftward shift of duration distributions for fixations after between-word landing (Fig. 6.16).

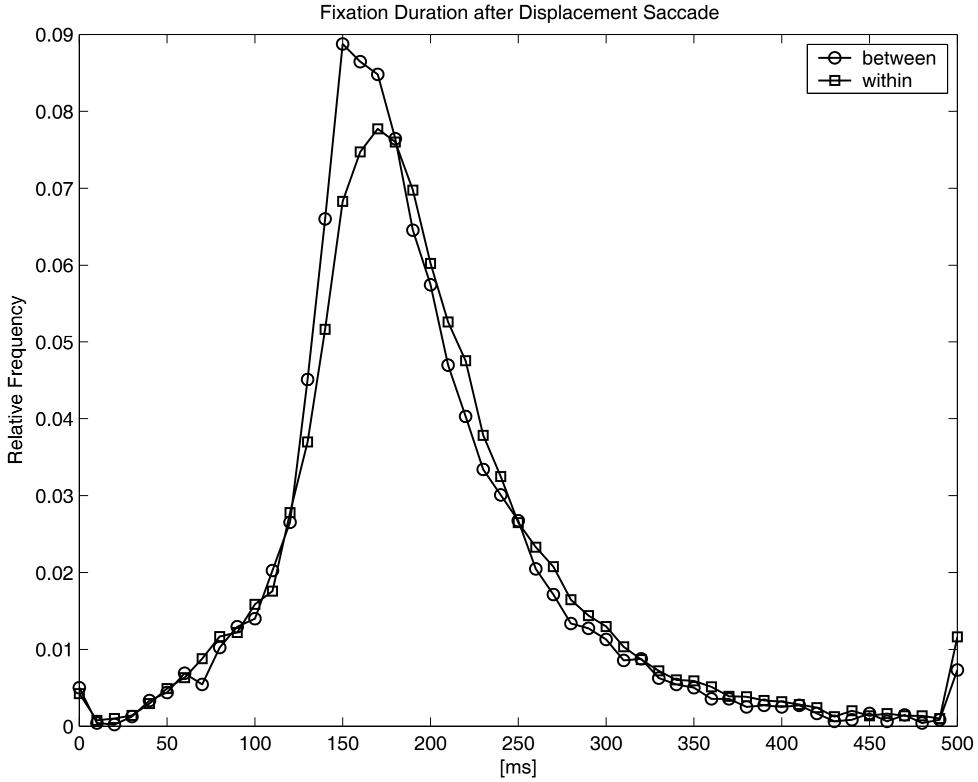

Fig. 6.16 Reading with recurrent sentence shifts experiment. Fixation duration distributions for fixations after displacement saccades leading to within-word landing shifts (squares) vs. between-word landing shifts (circles).

Recall that between-word landing shifts are more frequent if the eyes would have landed on a short word (Table 2.1, Fig. 2.12, p. 51). However, the length of the word the eyes *did* land on is not necessarily the same as the length of the word the eyes *would* have landed on without the shift (cf., Fig. 4.14, p. 117). Rather, it depends on the word material. Assuming that the duration of the experimentally induced mislocated fixation is influenced by the characteristics of the word that was actually fixated, rather than the anticipated word, it is therefore argued that the decreased duration after between-word landing shifts is not due to a word length effect.

Schematically, according to Eq. 8 (p. 152) any τ_C value that is smaller than F_L will generate an Fixation-Duration IOVP effect. Thus, if one would assign the 187 ms and/or 197 ms to τ_C and/or F_L respectively, the proposed mechanism would generate an

IOVP effect. The 10-ms difference would, however, not be sufficient to reproduce the strength of the empirical IOVP effect. In Sec. 6.1.3 (pp. 151) it was argued that, via the principle of efference copies, oculomotor errors are continuously monitored, suggesting that a mislocated fixation can be detected immediately after the end of the misguided saccade, allowing to start a new saccade program close to the beginning of the mislocated fixation. In the sentence-shift experiment, however, the gaze error was experimentally induced. Therefore, the decision about whether or not to initiate a corrective saccade in response to the mislocated fixation could be made only after a delay reflecting the time that is necessary to take in the information about where the fixation is located. The duration of the eye-brain lag is about 60 ms (cf., Sereno & Rayner, 2003). Consequently, the latency of saccades following experimentally induced mislocated fixations is longer than the assumed latency of saccades following “real” mislocated fixations. In sum, empirical data from the sentence-shift experiment lend support the assumption that mislocated fixations are, on average, shorter than well-located fixations.

6.4.2 Fixation Durations following Critical Saccades

In the previous section, critical fixations *n* were examined. In the present section, the following fixations *n*+1 are considered. Previously, landing position distributions for critical saccades were examined (Sec. 4.4.5.2, p. 118). For each word length × displacement condition combination the typical PVL phenomenon emerged (Fig. 4.15, p. 119). Likewise, the computation of IOVP curves for fixation durations following critical saccades[48] suggests that the temporal module of the visuo-oculomotor system has more or less “recovered” from the changes in landing positions created by the frequent sentence displacements (Fig. 6.17 as compared to Fig. 6.5b, p. 152).

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[48] As in Sec. 4.4.5.2 on landing position distributions, inter-word and intra-word critical saccades were jointly considered.

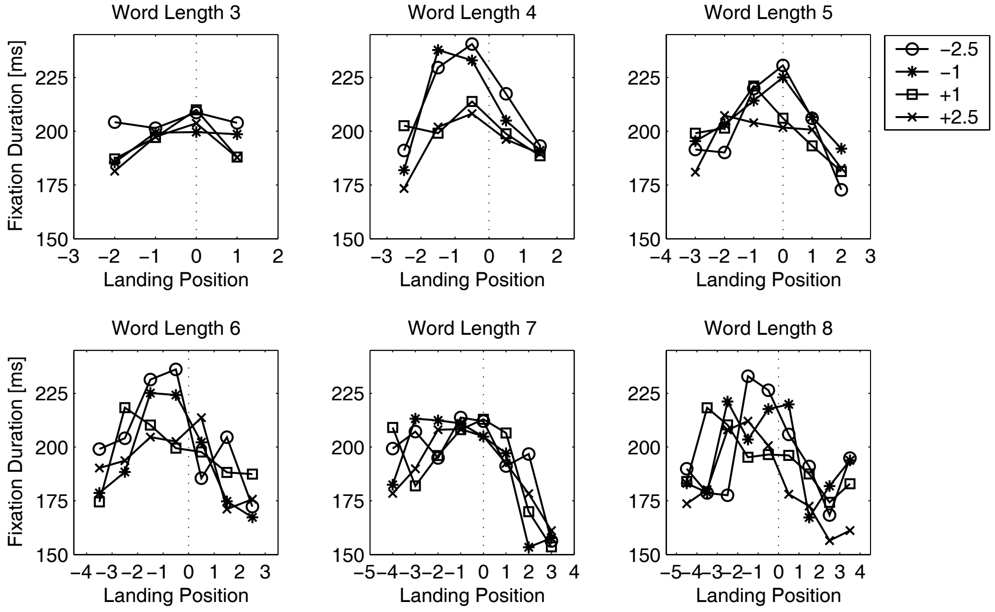

Fig. 6.17 Reading with recurrent sentence shifts experiment. Fixation-Duration IOVP effect for fixation durations after critical saccades. Data are plotted as a function of word length and shift condition, with each panel representing data for a given word length (3 through 8).

In some cases, there is an effect of shift condition (left vs. right shifts) on parameter *A*, the vertical offset of the IOVP curve; durations related to left-shifts are somewhat longer than durations related to right shifts (e.g., word length 4). Furthermore, in particular for word length 8, there is an effect of shift condition on parameter *C*, the horizontal offset of the IOVP curve.

6.5 Summary and Discussion

In Chapter 6, a mechanism underlying the IOVP effect for fixation durations was proposed (Sec. 6.1, pp. 141). The theoretical explanation was developed in two steps. First, it was assumed that mislocated fixations, i.e. fixations on unintended words due to saccadic errors, are more frequent close to word boundaries. Second, the assumption of a fast error-correction mechanism in response to a mislocated fixation implies a decrease of the mean fixation duration near word boundaries. With numerical methods based on experimental data it was demonstrated that the proposed mechanism for generating IOVP effects is quantitatively viable. These model-based analyses of experimental data have important implications for computational models of eye-movement control in reading (see Sec. 6.5.3 below).

6.5.1 Mislocated Fixations

Several cases of mislocated fixations were distinguished (Fig. 6.2, p. 145): failed skipping, unintended forward refixation, and undershot regression (undershoot cases), unintended skipping, failed forward refixation, overshot regression, and failed backward refixation (overshoot cases). Based on simulations with the SWIFT model, the magnitude of these different cases of mislocated fixations was explored in detail (Sec. 6.3.2, p. 157). Failed skipping turned out to be most prevalent.

6.5.2 Coupling Saccade Programs to Oculomotor Errors

Estimation of the fraction of mislocated fixations. A central part of the IOVP model introduced in the current chapter was the development of an algorithm to estimate the proportion of mislocated fixations as a function of word length and within-word landing position (6.1.2, p. 143). On the assumption of Gaussian distributed landing positions, the experimentally obtained distributions from within-word landing positions were extrapolated to neighboring words. The fraction of mislocated fixations was then computed as the proportion of overlapping probability relative to landing site probability. According to the calculations, more than 10% of all fixations could be mislocated (Table 10, p. 148). The frequency of mislocated fixations also varied dramatically with landing position and was highest close to word boundaries, that is at the beginning and end of words. The proposed algorithm was validated with simulations using the SWIFT model (6.3.1, p. 156). It should be noted that the algorithm is currently being refined based on an iterative approach (Engbert, Nuthmann, & Kliegl, in press). There, observed landing position distributions are iteratively decomposed into mislocated and well-located contributions. Taken together, the results presented here suggest that mislocated fixations might be very frequent and should not be neglected in data analysis and theoretical models.

An explanation for IOVP effects. As a new central theoretical claim, it was suggested that a new saccade program is started immediately if the intended target word is missed, leading to decreased durations for mislocated fixations as opposed to well-located fixations. As mislocated fixations are more frequent at the beginning and end of words, fixation durations exhibit an inverted U-shape when plotted as a function of landing position. Thus, an explanation for an effect which Vitu *et al.* (2001) concluded to be elusive was provided.

The overall probability of receiving a mislocated fixation was similar for all word lengths considered (Table 6.2, p. 148). Fig. 6.5a (p. 152) provides a more detailed picture by depicting the proportion of mislocated fixations as a function of both word length and landing position. For short words, the position-dependent relative proportions were apparently more evenly distributed across the word whereas for long words, misguided saccades mostly landed on word borders. According to the proposed explanation, the strength of the IOVP effect – as reflected by the slope of the fitted quadratic function – mainly depended on the difference of these proportions for the center of word as compared to the word borders. This difference was greater for long words as compared to short words. Thus, the IOVP effect was “stronger” for long words for both the empirical (Fig. 6.5b) and generated (Fig. 6.5c) data. Mathematically, this relationship was captured by parameter *B’* which systematically increased with word length (see Table 5.1, p. 125, for empirical data).

In principle, every fixation can be a mislocated fixation. Thus, the proposed mechanism predicts an IOVP effect for single-fixation, first-fixation, and second-fixation durations, and that is what we observed (Sec. 5.1.1 & Sec. 5.1.2). Given the available data, the approximations based on empirical data, however, do not allow to reproduce quantitative differences between these IOVP functions, such as the stronger curvature for first of two compared to single fixations. It is argued that a main factor contributing to the Fixation-Duration IOVP effect are mislocated fixations caused by saccadic errors. However, it is likely that there are other factors also contributing to the effect. First, in order to reproduce the IOVP effect for the first of multiple fixations as well as the fixation duration trade-off effect for two-fixation cases, the SWIFT model (Engbert *et al.*, 2005) had to be furnished with a saccade latency modulation (see Sec. 6.3.3, p. 162). Second, an IOVP effect was observed for the duration of the first of two consecutive fixations when the word was directly displayed in foveal vision and the initial fixation location was imposed (O’Regan & Lévy-Schoen, 1987). In such a paradigm, mislocated fixations cannot occur. Based on a recent series of isolated word recognition experiments it is therefore suggested that a part of the IOVP effect is not related to mislocated fixations but to perceptual-economy processes which favor longer fixation times at positions where greater amounts of information are anticipated (Vitu, Lancelin, & d’Unienville, submitted).

Implications for data analysis. Most psycholinguistic research uses fixation durations as a measure of processing time for the fixated word. Mislocated fixations are a substantial source of error variance for these conventional forms of data analysis because the word we are fixating on may not necessarily be the word we are currently processing. Obviously, removing or reassigning mislocated fixations could substantially increase the statistical power for detecting experimental effects.

6.5.3 Implications for Theoretical Models of Eye-Movement Control in Reading

Current theories on eye-movement control in reading have so far neglected IOVP effects, since experimental evidence was only recently provided (Vitu *et al.*, 2001). Oculomotor theories such as the strategy-tactics model by O'Regan (1990, 1992) predict that durations for single fixations do not depend on landing position within the word. Cognitive theories (e.g., Reichle *et al.*, 2003) assume that any difficulty in word processing would not only result in higher refixation probabilities but also longer fixation durations, resulting in U-shaped curves. The considerable success of cognitive models based on word processing may have misled some researchers to underestimate the importance of oculomotor processes. Empirical data and numerical analyses reported here suggest that consequences of error correction of mislocated fixations could be derived from a coupling between oculomotor and cognitive processes.

The mechanism proposed to account for the IOVP effect is generally compatible with both oculomotor and cognitive theories. Since the mechanism is based on error correction of mislocated fixations, a theoretical model compatible with this mechanism must specify an intended target word in order to detect a mislocated fixation and to initiate a fast error-correcting saccade program. Both cognitive models (e.g., Reichle *et al.*, 2003; Engbert *et al.*, 2005) and most oculomotor models (e.g., O'Regan, 1990; Reilly & O'Regan, 1998) assume that reading saccades are directed to a specific target word (see Yang & McConkie, 2004, for a good discussion on this issue). In oculomotor models, however, it is unclear whether a mislocated fixation needs to be corrected by another saccade, because eye movements are not driven by word identification, so that it is unclear if and how a mislocated fixation would have an impact on subsequent eye movements.

In cognitive models based on sequential shift of attentions (SAS), the occurrence of mislocated fixations itself might significantly impact upon the reading process. SAS models rely on word processing in serial order. Mislocated fixations, however, are a potential source of violation of serial order. For example, Reichle *et al.* (2003) incorporated McConkie *et al.*'s (1988) views of saccadic errors into the E-Z Reader model. Thus, the model predicts saccadic errors and, consequently, mislocated fixations. In the case of a mislocated fixation, however, the currently fixated word is not the attended word. Even though E-Z Reader can produce mislocated fixations, in its current version there is no mechanism to respond to the phenomenon. Thus, it is unclear whether E-Z Reader can account for the IOVP effect quantitatively. In principle, it is reasonable to assume that E-Z Reader could be furnished with an error-correcting mechanism. The quantitative fit of data needs to be established, of course. In addition, Reichle *et al.* (2003) underestimated the significance of mislocated fixations when they estimated that “the percent of such mistargeted saccades will be small” (p. 510). Estimations based on empirical data (cf., Table 6.2, p. 148) as well as numerical simulations with the SWIFT model (Table 6.3, p. 158) suggested that this is not the case. Moreover, a direct error correction mechanism, consistent with the type of word targeting in the E-Z Reader model, might turn out to be too strict for further processing. For example, in some cases the word receiving the mislocated fixation might even be a better choice than the intended target word or the saccade correcting the previous error might be no longer necessary due to parafoveal processing of the intended (but missed) word. Simulations with the SWIFT model showed that a failed skipping is not always corrected with a forward saccade to the word that the eyes originally had intended to fixate. Frequently, the virtual eyes proceeded with skipping that word because of parafoveal processing during the mislocated fixation (Sec. 6.3.2.2, pp. 159).

Ideas concerning the IOVP effect, as developed here, were implemented in the SWIFT model (see Sec. 6.3.3, pp. 162). The SWIFT model (Engbert *et al.*, 2005) operates on the concept of spatially-distributed processing of words. As a consequence, mislocated fixations mainly affect the model’s processing rates for particular words, but they do not have a major impact on the model’s dynamics.

7 Influence of Launch Site Distance

Besides word length, launch site distance is the most important “low level” visuomotor variable influencing measures of eye movements in reading. The large data set from the original reading experiment ($N = 245$) allowed orthogonal data sampling by both word length and launch site distance. Therefore, the following analyses examine the influence of launch site distance on OVP (Sec. 7.1), PVL (Sec. 7.3) and the Fixation-Duration IOVP effect (Sec. 7.2).

7.1 Optimal Viewing Position

Previous research showed that refixation probability for a given word length increases as the launch site increases (Vitu *et al.*, 1990; McDonald & Shillcock, 2004). Vitu *et al.* (1990) computed refixation probabilities as a function of initial landing position, but testing the effect of launch site was restricted to two relatively broad launch site categories (near: 1-5 letters left of the word, and far: 6-10 letters left of the word). In contrast, McDonald & Shillcock (2004) tested 5 launch site distance categories ([1,2] through [9,10]), but restricted their analyses to *overall* refixation probability, i.e. they did not consider the strong dependence on initial landing position. The following analyses extend the existing findings in that they demonstrate how, for a given word length, the parameters of the parabolic refixation probability function vary as a function of launch site distance. The influence of launch site distance is illustrated in Fig. 7.1, which shows refixation probability curves for 4-, 6- and 8-letter words following launch sites at different distances to the left of the word.

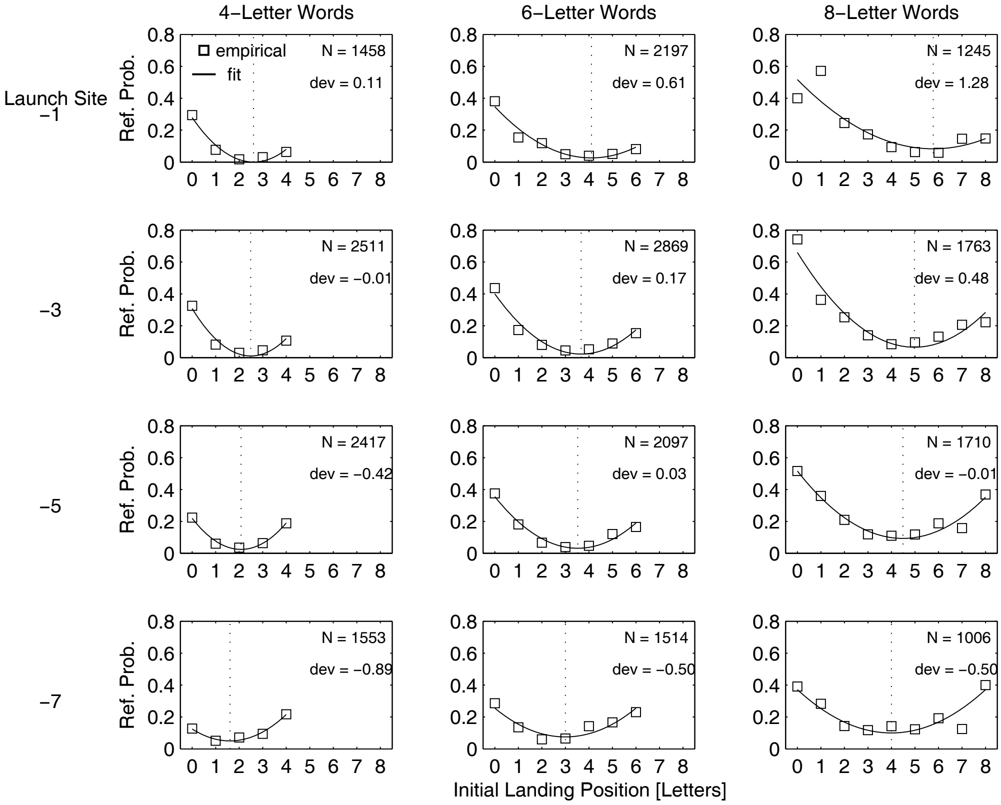

Fig. 7.1 Refixation probability curves for different word lengths (4, 6, 8), and launch site distances (-1, -3, -5, -7). Also presented is the best fit to $y = A + B(x - C)^2$. The dotted vertical line represents the OVP (C), i.e. the location of minimum refixation probability (A). A *positive* deviation value ("dev") denotes a minimum refixation probability *right* of word center whereas a *negative* value denotes a minimum *left* of word center.

Fig. 7.2 summarizes the influence of both word length and launch site distance on the parameters of the quadratic refixation function in that it displays fit parameters for the whole word length (4 through 9) × launch site (1 through 10) spectrum considered in this analysis. Different word lengths are represented by different symbols. The launch site distance effect was captured by fitting a linear regression function to the data. Because there is only a tiny influence of word length on parameter *C'* only one linear regression function was fitted for data across all word lengths (Fig. 7.2c).[49] For parameters *A*, and *B'*, however, data were fitted separately for each word length category.

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[49] However, when ordinary least squares regression (function 'polyfit' in MATLAB) is used to model parameter *C* as a function of launch site distance, outliers (here, apparently caused by 8- and 9-letter words) exert a rather large influence. Therefore, a robust linear regression (function 'robustfit' in MATLAB) was used.

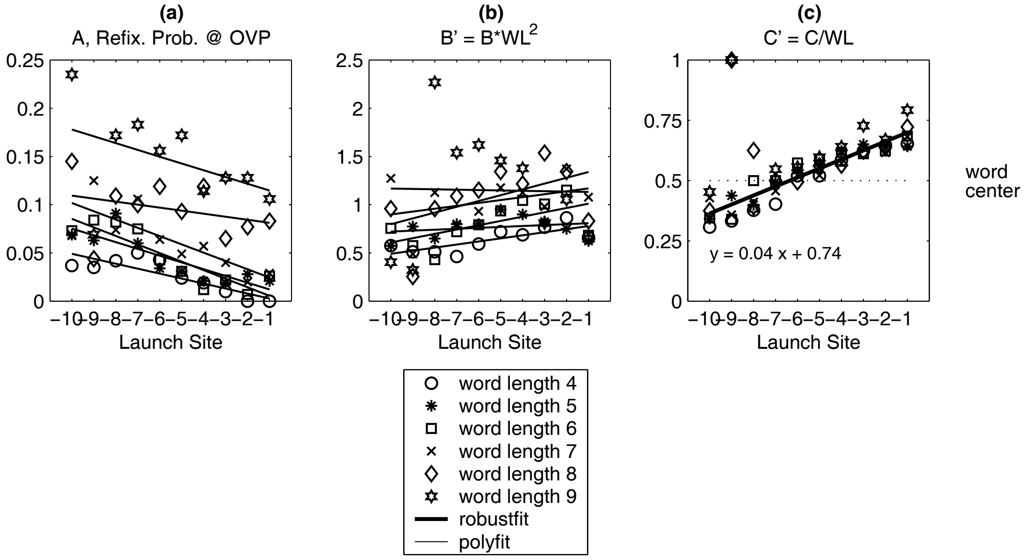

Fig. 7.2 Quadratic fit to refixation probability curves: Parameters *A* (panel a), *B'* (panel b), and *C'* (panel c) as a function of word length and launch site distance.

Interestingly, parameter *C'* is clearly modulated by launch site distance, computed relative to the beginning of the word: For short distances, the OVP is right of word center while the OVP is left of word center for longer launch site distances. Thus, the further away the target word, the more the OVP shifts to the left (Fig. 7.2c). While existing literature consistently reports an OVP close to word center, the current analysis demonstrates that the OVP is systematically influenced by launch site distance. Only when *C'* is averaged across all word lengths and launch site distances, the OVP translates to the center of word (*C'* = 0.55). As for parameter *B'*, reflecting the penalty of not fixating at OVP, no clear launch site effect can be observed (Fig. 7.2b; cf., Vitu *et al.*, 1990).[50] There is, however, a launch site effect on parameter *A* which reflects the refixation probability at OVP: Refixation probability at OVP increases as launch site distance increases.

As for word length, the current analyses replicate and extend previous analyses where data were not controlled for launch site distance (Sec. 3.1, pp. 62). The penalty of not fixating at OVP, as reflected in parameter *B'*, increases as word length increases (Fig. 7.2b). There is not much of a word length effect on *C'*. There is, however, a

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[50] The data might indicate a slight tendency of *B'* to decrease with increasing launch site – a finding that is somewhat counterintuitive.

tendency for a word length effect on parameter *A*: Refixation probability at OVP increases as both word length and launch site distance increase.

The observed launch site effects are likely to be attributable to parafoveal preprocessing during fixations in reading (cf., Vitu *et al.*, 1990). There is a large body of evidence for *parafoveal preview benefit*; when the reader fixates word *n*, information is obtained parafoveally about word *n* + 1, which facilitates its subsequent (foveal) processing (see Rayner *et al.*, 1996, with further references). Increasing launch site distance translates into progressively less parafoveal information about the target word. Fewer letters are perceptible when the previous fixation is far from rather than near to the target word. Thus, a long launch site distance may make a refixation more likely.

To summarize, parafoveal preprocessing – measured in launch site distance – has a rather global effect on refixation probability. The minimum refixation probability at OVP increases with increasing launch site distance; this is combined with a leftward shift of the OVP. However, launch site distance appears not to change the slope of the refixation probability curve.

7.2 Fixation-Duration IOVP Effect

Next, it is investigated how launch site distance influences the three parameters of the quadratic Fixation-Duration IOVP function. Radach & Heller (2000) were the first to report related results. In their data, fixation position and launch site distance appeared to contribute independently to the variability of fixation durations. In a central paper on Fixation-Duration IOVP effects, Vitu *et al.* (2001) presented Single-Fixation Duration IOVP curves as a function of two relatively broad launch site categories (e.g., for Adults-Set 1 near: 1-5 letters left of the word, and far: ≥ 6 letters left of the word). They replicated the findings by Radach & Heller (2000) in that they showed that the effect of launch site distance mainly consisted in a vertical displacement of the IOVP function. The effect was termed "Saccade Distance effect" and was explained in terms of peripheral preview (Vitu *et al.*, 2001).

The current analyses considered single fixations on 3- through 8-letter words following launch site distances -1 through -6, in 1-letter steps. Fig. 7.3 shows a subset of the obtained IOVP curves.

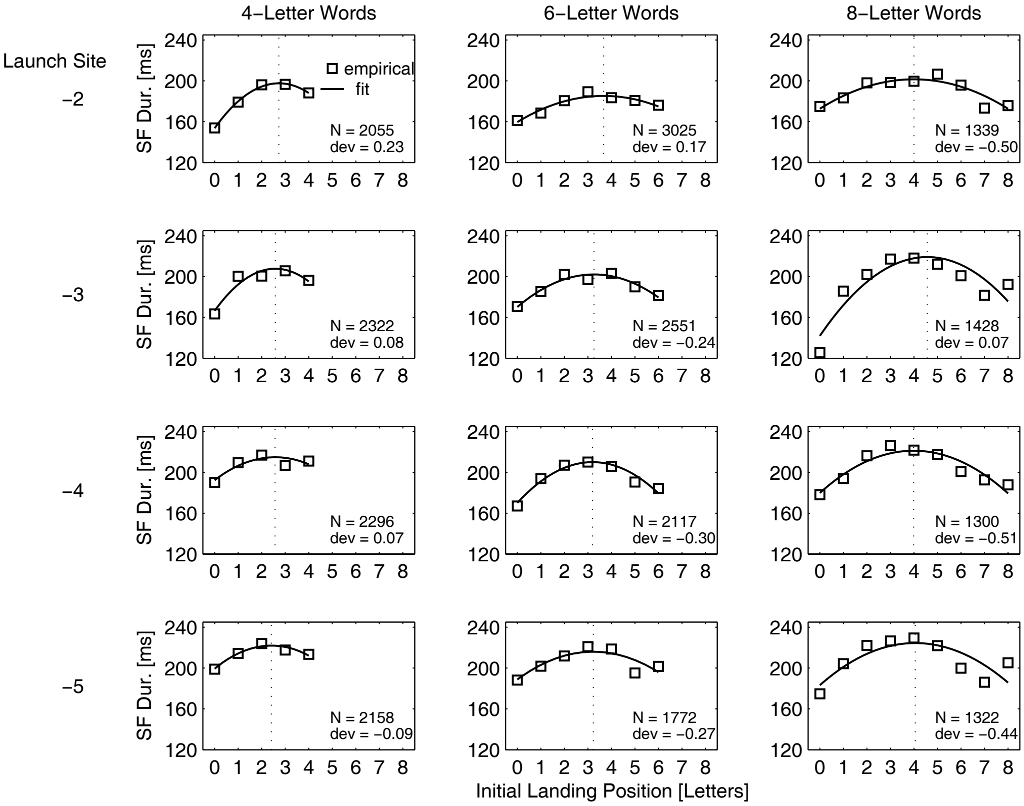

Fig. 7.3 Single-Fixation IOVP curves for different word lengths (4, 6, 8) and launch site distances (-2, -3, -4, -5). Also presented is the best fit to $y = A - B(x - C)^2$. The dotted vertical line represents C, i.e. the location of maximum fixation duration (A). A *positive* deviation value ("dev") denotes a maximum fixation duration *right* of word center whereas a *negative* value denotes a maximum *left* of word center.

Fig. 7.4 visually depicts the parameters of the fitted quadratic IOVP curves as a function of word length and launch site distance. Parameter *A*, the vertical offset of the IOVP function, reflects the fixation duration maximum which clearly increases with increasing launch site distance (Fig. 7.4a). As for the strength of the IOVP effect, reflected in parameter *B'*, there appears not to be a very systematic launch site effect (Fig. 7.4b). Parameter *C'*, the horizontal offset of the curve, reflects the fixation location of maximum fixation duration *A*. Launch site distance has no effect on parameter *C'* (Fig. 7.4c). As far as word length is concerned, the current data more or less replicate results presented in Chapter 5. There is a linear relationship between word length and parameter *B'*: The strength of the IOVP effect increases as word length increases. The word length effects on parameters *A* and *C'*, however, are less systematic.

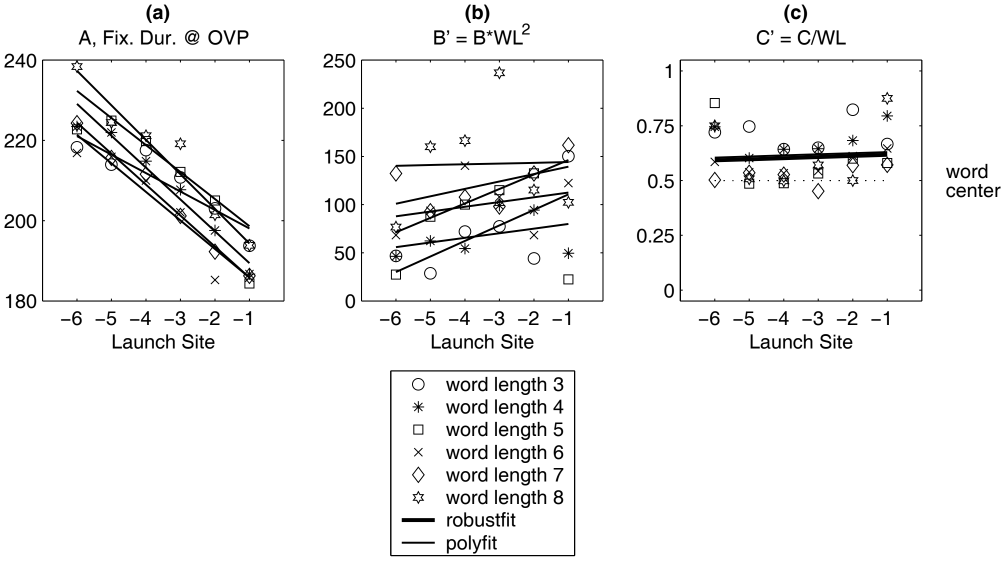

Fig. 7.4 Quadratic fit to Single-Fixation IOVP curves: Parameters *A* (panel a), *B'* (panel b), and *C'* (panel c) as a function of word length and launch site distance.

To summarize, the current data replicate the Saccade Distance effect in that they show that the effect of launch site distance mainly consists in a vertical displacement of the IOVP function (cf., Radach & Heller, 2000; Vitu *et al.*, 2001).

7.3 Preferred Viewing Location

In the current section, it will be explored in detail how landing position distributions are influenced by launch site distance. Progressive inter-word saccades (Sec. 7.3.1), regressive inter-word saccades (Sec. 7.3.2), and refixations (Sec. 7.3.3) are considered separately.

7.3.1 Progressive Inter-Word Saccades

In an influential paper, McConkie *et al.* (1988) showed that – for landing positions on words following progressive inter-word saccades – the preferred viewing location (see Chapter 4, pp. 100) is the maximum point in a distribution of all fixations on the word, which they referred to as a composite distribution. This composite distribution depends on the *center-based launch site distance,* that is the distance between the launch site of the last saccade and the center of the target word (see also Radach & Kempe, 1993; Radach & McConkie, 1998; Rayner *et al.*, 1996).

There is consensus that landing positions on words following progressive inter-word saccades are primarily determined by the launch site distance (Sec. 7.3.1.1). However, additional effects have been observed. Radach and McConkie (1998) reported additional smaller effects due to word length and position of the word on the line of text. Furthermore, there are controversial findings as to whether landing positions are affected by the duration of the prior eye fixation (Sec. 7.3.1.1.3, pp. 189), or cognitive variables like word frequency or the informativeness of the initial bigram or trigram of the word (cf., Sec. 8.1, pp. 211). In the following sections, hypotheses regarding these influences are tested for the present data set (Exp. 1, $N = 200$).

7.3.1.1 Five basic visuomotor principles (McConkie *et al.*, 1988)

McConkie *et al.* (1988) explicated theoretical assumptions on landing positions within words with five basic visuomotor principles:

(I) reading saccades have a functional target location: the center of the word;

(II) a saccadic range error occurs which produces an error in the mean landing site that is a linear function of the distance of the launch site form the functional target location;

(III) the influence of the saccadic range error is lessened following longer eye fixations;

(IV) perceptuo-oculomotor variability occurs in the form of random placement error;

(V) such perceptuo-oculomotor variability increases with the distance of the launch site from the target.

Several models of eye-movement control in reading have largely incorporated McConkie *et al.*'s suggestions in order to account for saccade programming to words once the word target has been selected (Reichle *et al.*, 1999, 2003; Reilly & Radach, 2003; see also Reilly & O'Regan, 1998). Therefore, for further development of our own SWIFT model (Engbert *et al.*, 2005), the validity of the principles outlined above has been tested with the following analyses based on a comprehensive set of German reading data.

7.3.1.1.1 Saccadic range error (Principle II)

As the launch site moves further from the target word, the distribution of landing positions shifts to the left. This systematic shift has been attributed to low-level oculomotor processes and was interpreted in terms of a *saccadic range error* (SRE, McConkie *et al.*, 1988, referring to Kapoula, 1985; Poulton, 1981). When the eyes are close to a target word, thus requiring very short saccades, the SRE will produce an overshoot of the center of the target word, whereas when the eyes are further away, thus requiring longer saccades, saccades tend to undershoot the center of the target word.

The relatively broad composite distributions displayed in Fig. 4.1 (p. 101) were decomposed by splitting the data by launch site distance (Fig. 7.5). Note that only initial fixations were considered to facilitate a direct comparison with the widely-cited English data by McConkie *et al.* (1988) whose analyses were based on a sample of 66 college students. Table 7.1 presents the results of fitting normal curves to the launch-site contingent landing-position distributions, including means, standard deviations, average residuals (i.e., mean of the absolute values of the differences between the best-fit curve and each empirical data value; cf., McConkie *et al.*, 1988), and the total number of fixations in the distributions.

Table 7.1 Means and standard deviations (SD) of landing position distributions fitted to the normal curve.

Launch	4-letter Words				5-letter Words				6-letter Words				7-letter Words				8-letter Words			
Site	Mean	SD	Res	N	Mean	SD	Res	N	Mean	SD	Res	N	Mean	SD	Res	N	Mean	SD	Res	N
-1	3.3	1.3	0.005	1094	3.6	1.4	0.011	1407	3.7	1.5	0.011	1653	3.8	1.6	0.014	1584	4.1	1.8	0.017	887
-2	2.9	1.2	0.007	1843	3.1	1.4	0.014	2238	3.3	1.7	0.012	2749	3.3	1.6	0.016	2711	3.7	1.7	0.016	1343
-3	2.7	1.5	0.004	2068	2.9	1.5	0.011	2432	3	1.6	0.009	2150	3.1	1.7	0.01	1883	3.5	1.6	0.015	1367
-4	2.4	1.6	0.008	1980	2.4	1.6	0.009	2284	2.8	1.6	0.007	1787	2.9	1.6	0.014	1412	3.2	1.7	0.014	1248
-5	1.9	1.7	0.008	1892	2.1	1.9	0.009	2042	2.2	2.1	0.004	1592	2.3	1.8	0.012	1447	2.8	1.8	0.009	1338
-6	0.9	2.3	0.009	1636	1.5	2.1	0.005	1676	1.6	2.2	0.013	1415	1.7	2.1	0.013	1213	2	2.1	0.011	1057
-7	0	2.7	0.004	1198	0.2	2.7	0.005	1309	1.2	2.1	0.007	1067	1.1	2.3	0.011	995	1.6	2.2	0.01	747

Note. Launch site is measured in letter positions relative to the space immediately to the left of the word, designated landing position zero. Negative numbers indicate positions to the left of that space. 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.

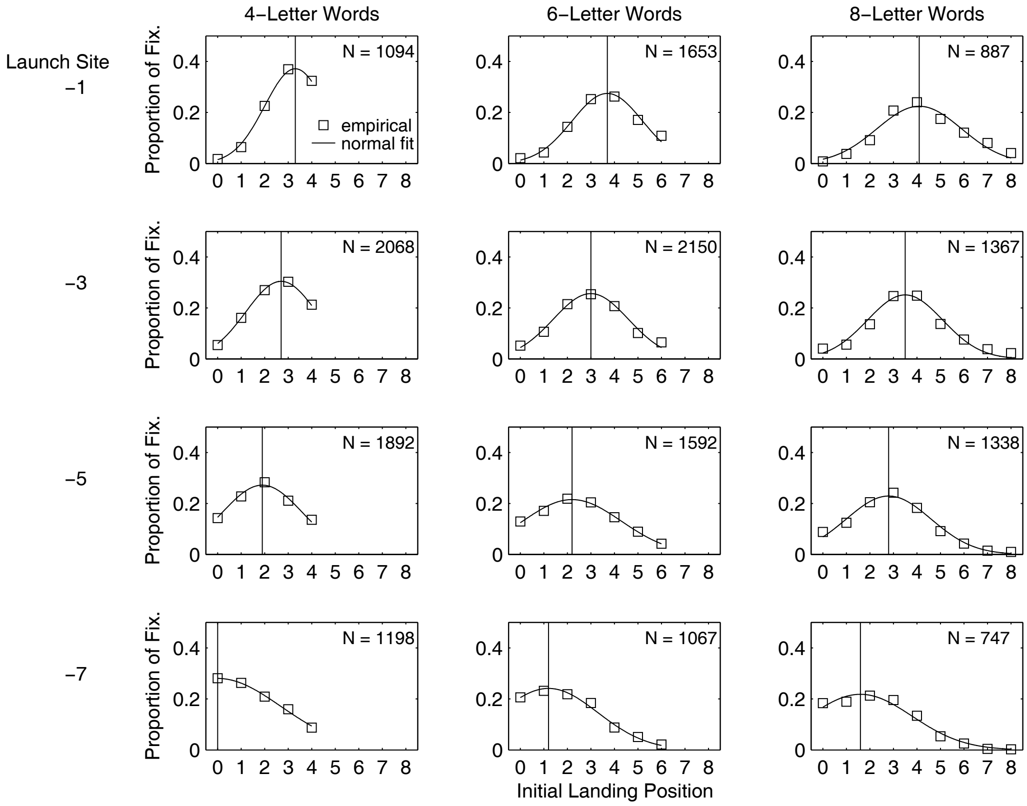

Fig. 7.5 Landing position distributions for different word lengths and launch site distances. Also presented is the best-fitting normal curve for each distribution. Vertical lines represent the means of the fitted curves.

The landing site distributions were in good agreement with those reported by McConkie *et al.* (1988): (1) The distributions were approximately normal in shape, (2) distribution means were located near word centers, (3) distributions were shifted towards the beginnings of the words, and (4) they became more variable as the distance between the launch sites and the intended target word increased (Fig. 7.5).

In Fig. 7.6, estimated mean landing site was plotted against launch site for 4-8 letter words. For each word length the relationship is linear, reflecting the so-called “landing position function” (Radach & McConkie, 1998). The *y*-intercepts of the fitted regression functions clearly increase with word length. Thus, for a given launch site, when computed relative to word beginning, we find a small effect of word length on mean landing site with an increased mean landing site for longer words (Fig. 7.6). Thus, when launch site is held constant, the average initial saccade into a word is longer for longer target words. However, the effect of word length is much smaller than the effect of launch site distance. Radach & McConkie (1998), also reporting a small word length effect, interpret the additional word length effect as a “center of gravity” phenomenon

(Findlay, 1982), modulating the launch position effect: The landing position saccades can be influenced by the presence of further elements in the critical visual configuration, in the present case additional letters belonging to the same target word.

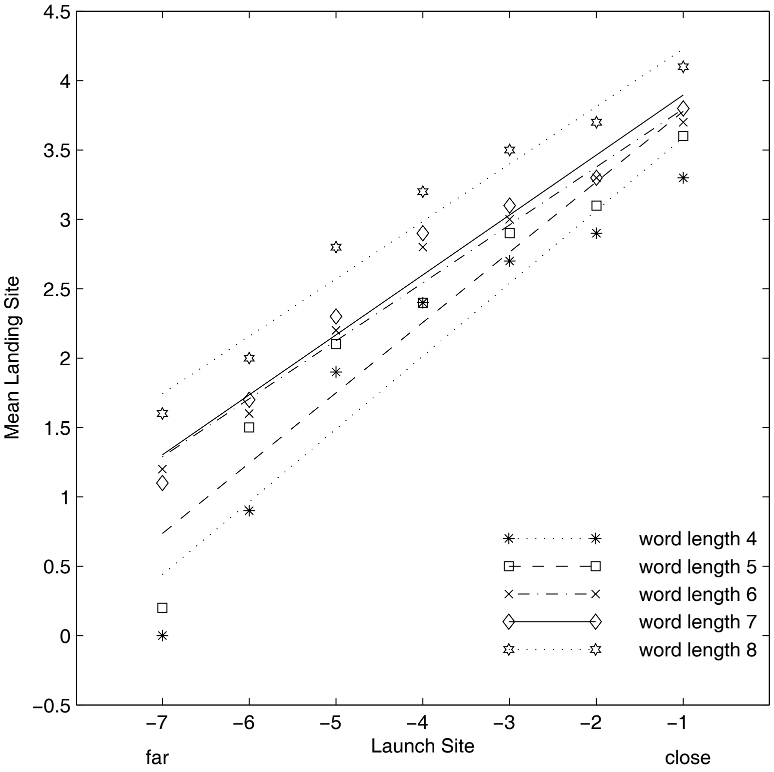

Fig. 7.6 Estimated means of landing site distributions as a function of launch site distance, computed relative to the *beginning* of a word, for words of different lengths. Best fit linear functions are also presented for each word length.

However, when both launch sites and mean landing sites are computed relative to the *center* of a word, the regression lines come much closer together (Fig. 7.7) suggesting that word center is the true target location within a word (McConkie *et al.*, 1988).

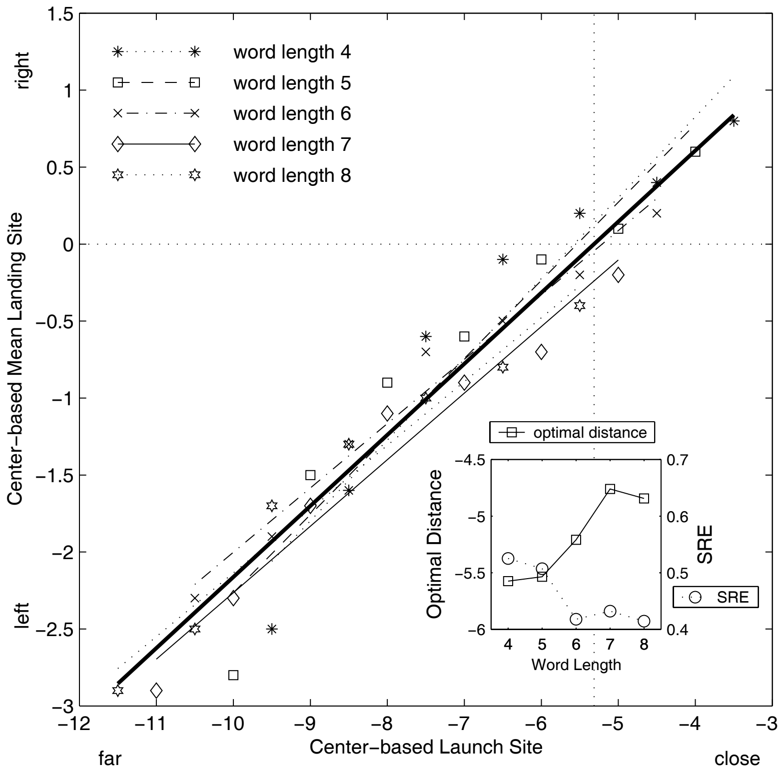

Fig. 7.7 Estimated means of landing site distributions as a function of launch site for words of different lengths. Distances are from the *center* of the word. On the *y*-axis, word center is represented by 0 value while negative values represent mean landing sites located left of word center. Best fit linear functions are also presented for each word length.

Still, the small word length effect evident from Fig. 7.6 reappears in Fig. 7.7. For each one-letter increase in word length, the average increase of the intercepts of the regression lines in Fig. 7.6 was smaller than 0.5 letters[51]. Therefore, for a given center-based launch site distance (Fig. 7.7), for long words the mean landing site is somewhat farther away from word center than for short words reflecting a more pronounced undershoot tendency for longer words. Still, since the word length effect was small, one regression function was fitted to all empirical data points (see bold line in Fig. 7.7, robust linear regression). This function reflects the average saccadic range error as well as the average optimal center-based launch site distance. For each one-letter increment in center-based launch site distance, the subsequent landing position within the target word moved about half a letter further towards the beginning of the word (i.e., with a mean of 0.47 letters across different word lengths, range: 0.41 to 0.53). This is the

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[51] First, note that center-basing is done in 0.5-letter increments. Second, the center-basing procedure does not change the slopes of the fitted linear regression functions; rather, it leads to a vertical and horizontal displacement of the regression lines.

saccadic range error. In addition, the mean of the landing position distribution is accurate (i.e., it equals the center of the target word), when the launch site is about 5.4 letters to the left of the center of the target (range: 4.8 to 5.6, Fig. 7.7). This is the average optimal center-based launch site distance; for saccades coming from this region, undershoots and overshoots are balanced.[52]

McConkie *et al.* (1988) computed an optimal center-based launch site distance of 6 to 7 letters. One reason for the observed discrepancy was that the fitting procedure developed for the present analyses yielded a much better fit to the present data than the fits reported by McConkie *et al.* (1988) for their data. For word lengths 4 to 8, averaged across different launch sites, mean residuals were 0.029, 0.022, 0.014, 0.015, 0.021 yielding an overall mean of 0.020 (computed from Table 1 in McConkie *et al.*, 1988). The corresponding values for the current fitting procedure were considerably smaller: 0.006, 0.009, 0.009, 0.013, 0.013, yielding an overall mean of 0.010 (computed from Table 7.1). In particular, McConkie *et al.*'s fit tended to underestimate the mean landing site for close launch sites and tended to overestimate the mean landing site for far launch sites. For medium launch sites, however, the German data indeed showed a stronger undershoot bias than the English data. Taken together, this led to a reduced optimal center-based launch site distance in the data reported here.

As for the saccadic range error, expressed by the slopes of the linear regression functions in Fig. 7.7, the current data largely replicate the data reported by McConkie *et al.* (1988): The executed saccades tend to overshoot (or undershoot) by approximately one half of a character space for each character space that the center of the intended target deviates from the optimal distance.

7.3.1.1.2 Random placement error (Principles IV & V)

There is an additional random error component, characterized by the standard deviation of the landing site distribution. This "random placement error" (McConkie *et al.*, 1988) increases as the launch site moves further from the center of the target word (Fig. 7.8), but this is a non-linear relation. McConkie *et al.* (1988) fit these data to a curve of the form $y = A + B \cdot x^3$, where $A = 1.318$ and $B = 0.000518$ (see Fig. 7.8). The non-linear launch site effect on the random placement error is stronger for the German compared to the English data (see Fig. 7.8).

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[52] Note that we do find a small effect of word length on both the SRE and the optimal center-based launch site distance, both decreasing with increasing word length.

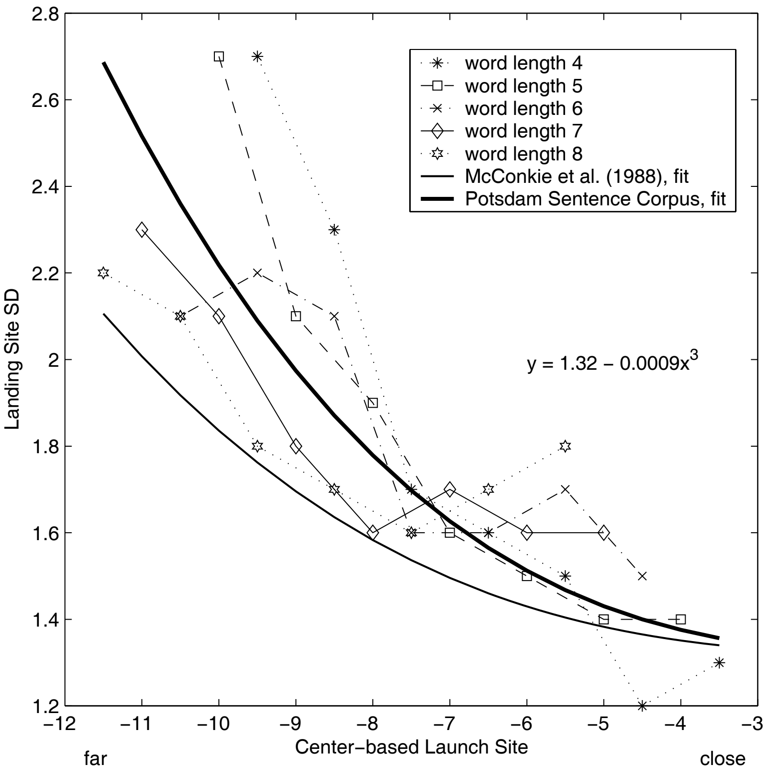

Fig. 7.8 Estimated standard deviations of landing position distributions for different word lengths and launch sites, measured as distance from the center of the word.

Interestingly, McConkie *et al.* (1988) found that the standard deviation did not vary with word length. For the present data, however, we observe a word length effect interacting with launch site: The launch site effect is stronger for shorter words. More specifically, for *close* center-based launch site distances there is a tendency for smaller standard deviations for shorter words whereas for *far* distances standard deviation is lowest for longer words.

7.3.1.1.3 Influence of the duration of the previous fixation (Principle III)

Of special theoretical interest is the influence of the duration of the previous fixation, the 'latency' of the initial saccade on oculomotor errors. Radach & McConkie (1998) further extended the work by McConkie *et al.* (1988) in that they derived and tested four hypotheses with differing predictions on that issue. First, and most "popular" is the so-called ***convergence hypothesis*** suggesting that landing positions should *converge* towards the word center (the OVP) after longer fixations. Second, the ***preprocessing hypothesis*** predicts that initial fixation positions within words are shifted to the *right* following longer preceding fixations while, third, the ***negative preprocessing hypothesis*** predicts a shift to the *left*. Fourth, the ***no relation hypothesis*** predicts that the duration of the preceding fixation is irrelevant for the following fixation position. Data by McConkie *et al.* (1988) lend somewhat support in favor of the convergence hypothesis. Therefore, Principle III was incorporated in the E-Z Reader model (Reichle *et al.*, 1999).

To facilitate a direct comparison with the data presented by McConkie *et al.* (1988), their analysis scheme was adopted for the following analysis. In Fig. 7.9, a given symbol (e.g., circle) stands for a particular center-based launch site category (e.g., 5-6) while full symbols represent long words (WL 7-8) and open symbols short words (WL 5-6). Each data point in Fig. 7.9 represents an estimated mean and/or standard deviation, based on a sample size between 282 and 5120, with the largest sample sizes appearing in the two middle fixation duration categories. First, the data replicate the launch site distance effect: With increasing launch site distance, the mean of the landing position distribution moves leftward (Fig. 7.9a) and the standard deviation increases (Fig. 7.9b). Furthermore, because mean landing site is not center-based in this analysis (due to data pooling across two adjacent word lengths), we inevitably observe a word length effect on mean landing site (Fig. 7.9a). In addition, except for short launch site distances (5-6), there is also a word length effect on landing site standard deviation (Fig. 7.9b) with higher standard deviation for shorter words.

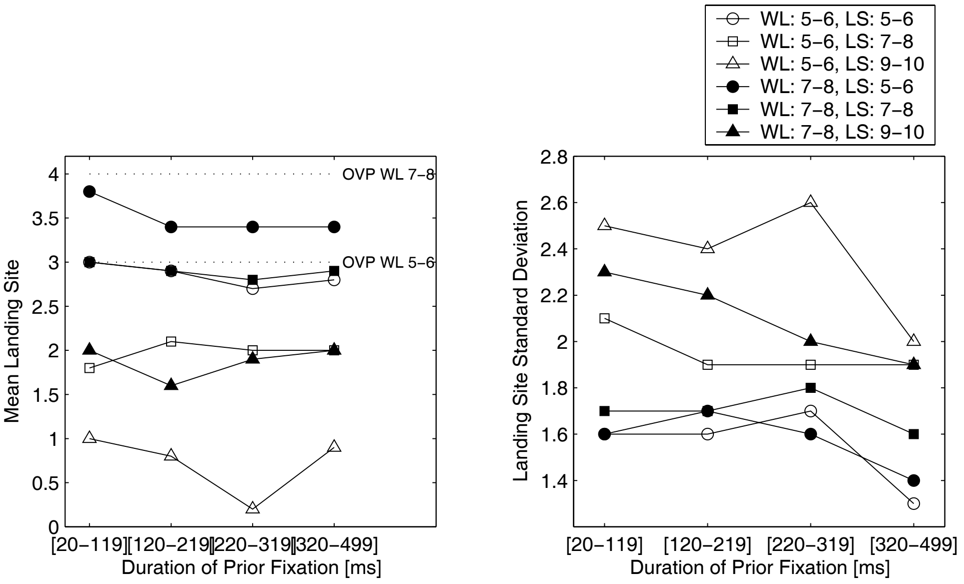

Fig. 7.9 Estimated means (a) and standard deviations (b) of the landing site distributions following fixations of different durations for different word length-center-based launch site combinations.

However, the current analysis reveals information about the additional influence of the duration of the previous fixation. The standard deviation decreases with longer fixation durations (Fig. 7.9b). Thus, the duration of the preceding fixation affects the "random placement error" (cf., Sec. 7.3.1.1.2) which is the source of error that produces the Gaussian shape of the landing position distribution and is indexed by the standard deviation of the distribution. The decreased "random placement error" after longer fixation durations in all likelihood reflects the natural lack of precision in saccade programming in cases with limited response times. With other word, precision in saccade programming is greater following longer saccade latencies.

However, an examination of Fig. 7.9a indicates that the pattern of results is considerably less clear when mean landing site is considered. What is clear is that the current data, unlike the data reported by McConkie *et al.* (1988), do not support the *convergence hypothesis*: Landing positions do not *converge* towards OVP after longer fixations (Fig. 7.9a, OVPs added as dotted horizontal lines). Interestingly, careful analyses employed by Radach & Heller (2000; see also Radach & McConkie, 1998) on the data produced by four German readers lend very specific support to the ***negative preprocessing hypothesis***: Only when the preceding fixation was a ***refixation*** on the last word (as opposed to single fixations and skippings) there appears to be a relation between its duration and the following landing position, with shorter fixations (indicating less processing on the prior word) associated with saccades that bring the eyes further into the next word.

The present analyses[53] (Fig. 7.9a) might also suggest that there is a tiny tendency towards a leftward shift of mean landing site following longer fixations. However, this effect appears to be neither strong nor very systematic. Therefore, neither Principle III, reflecting the convergence hypothesis, nor a principle reflecting the negative preprocessing hypothesis were incorporated into the most recent version of the SWIFT model (Engbert *et al.*, 2005).

In sum, as far as Principle III is concerned, the findings reported by McConkie *et al.* (1988) could not be replicated for the current data set. McConkie *et al.* (1988) had found that landing site standard deviation was not influenced by prior fixation duration while mean landing sites converged toward a point slightly to the left of word center.

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[53] It should be acknowledged that Radach & McConkie (1998) point to two methodological problems related to the employed analysis. Foremost, it is critical to set general margins for short vs. long fixations: A fixed range of fixation durations (as used both by McConkie *et al.*, 1988, and in the present analysis) creates the possibility that subjects with relatively low or high mean fixation durations are misrepresented (see Radach & McConkie, 1998).

The current data, however, support the hypothesis that variance in landing position distributions is reduced following longer fixations while mean landing site appears not to systematically vary with prior fixation duration.

7.3.2 Regressive Inter-Word Saccades

In the classic paper by McConkie *et al.* (1988) analyses were restricted to initial fixations following progressive inter-word saccades. In the current section, the influence of launch site distance is investigated for regressive inter-word saccades (cf., Radach & McConkie, 1998). In the case of inter-word regressive saccades, the launch site is to the right of the target word. Therefore, launch site distance was computed relative to the *end*, rather than the beginning, of the word the eyes regressed to. Launch site distances have positive values with the minimum being 0 – the space beyond the right border of the target word (cf., Radach & McConkie, 1998). Fig. 7.10 shows a subset of distributions obtained after orthogonal data sampling by word length and launch site distance.

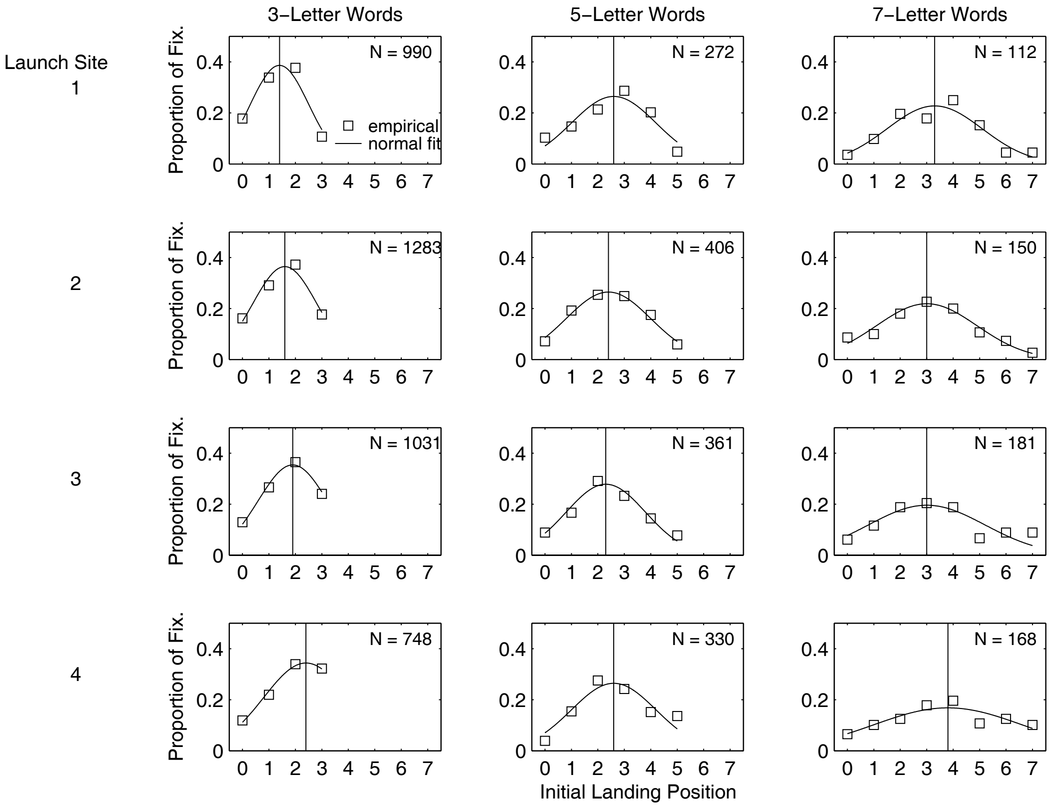

Fig. 7.10 Regressive inter-word saccades. Landing position distributions for different word lengths and launch site distances. Launch site is defined as letter position relative to the space *following* the fixated word. Also presented is the best-fitting normal curve for each distribution. Vertical lines represent the means of the fitted curves.

For 3-letter words, receiving the most regressive inter-word saccades (Table 4.2, p. 104), we observe a systematic rightward shift of landing position distributions with increasing launch site distance: The farther away the target the stronger the tendency to undershoot the center of the word and thus landing right of word center. Fig. 7.11 systematically explores this relationship by plotting mean landing site against launch site. Compared to the analysis of initial saccades into words (Sec. 7.3.1.1.1, pp. 183), the number of cases available for analysis of regressive inter-word saccades is greatly reduced. Specifically, there were few data points for long words, longer launch site distances as well as for launch site distance 0. Therefore, analyses were restricted to 3- to 7-letter words and launch site distances ranging from 1 to 6. Each point in Fig. 7.11 represents an estimated mean based on a sample size between 1283 (WL 3, LS 3) and 48 (WL 7, LS 6).

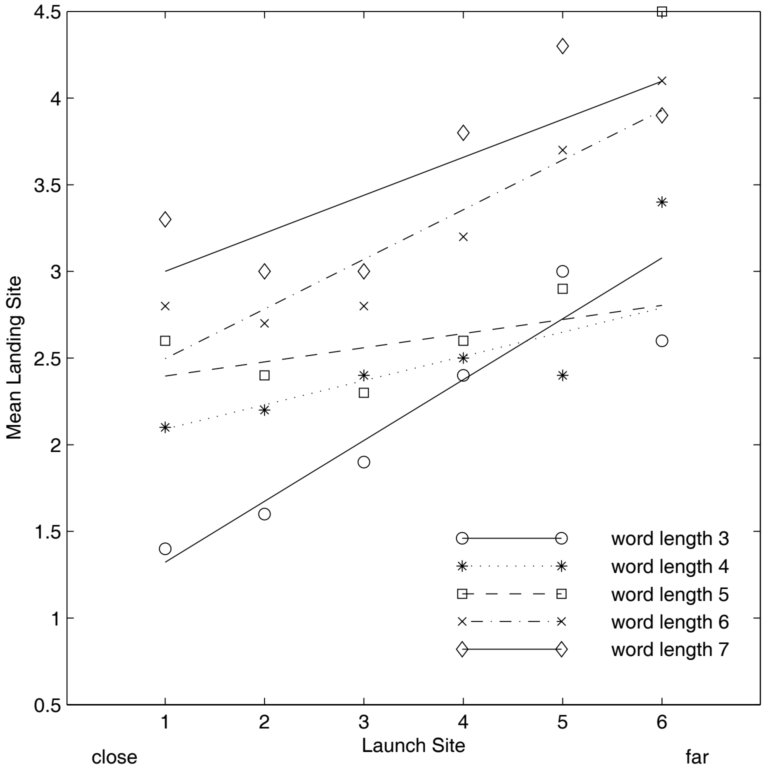

Fig. 7.11 Regressive saccades targeting 3- to 7-letter words. Estimated means of landing site distributions for inter-word regressive saccades as a function of launch site distance, computed relative to the *end* of a word, for words of different lengths. Best fit linear functions are also presented for each word length.

Visual inspection of Fig. 7.11 suggests that, across different word lengths, the linear relationship between launch site and mean landing site is less clear for regressive inter-word saccades as compared to progressive inter-word saccades. Still, linear regression functions were fitted to the data. In a next step of analysis, both launch sites and mean landing sites were computed relative to the *center* of a word (Fig. 7.12). To facilitate comparison with inter-word progressive saccades (Fig. 7.7), the same scaling as in Fig. 7.7 was applied to the *y*-axis in Fig. 7.12.

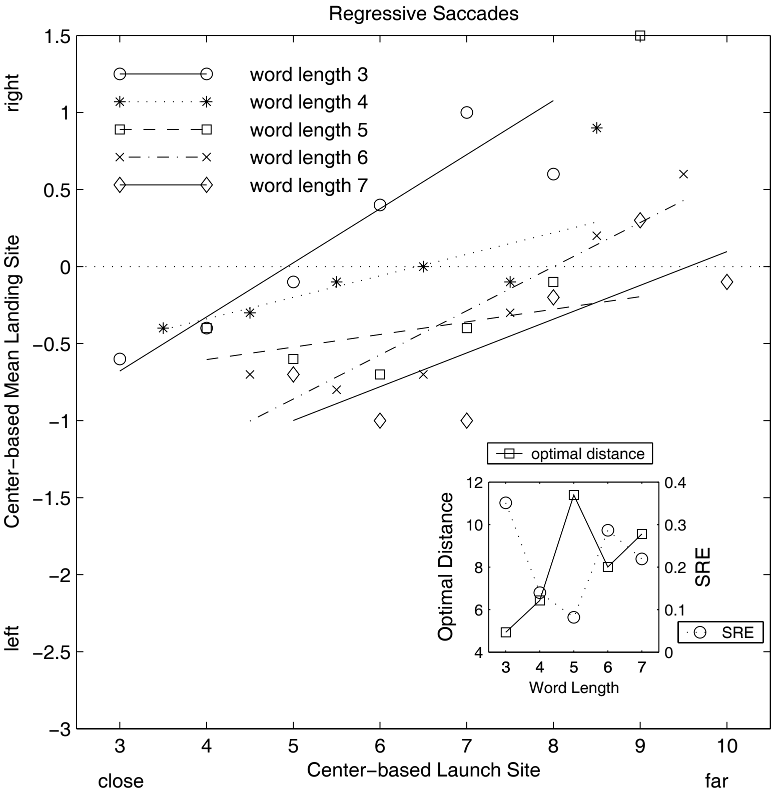

Fig. 7.12 Regressive saccades targeting 3- to 7-letter words. Estimated means of landing site distributions as a function of launch site for words of different lengths. Distances are from the center of the word. On the *y*-axis, word center is represented by 0 value while negative values represent mean landing sites located left of word center. Best fit linear functions are also presented for each word length.

Three findings are of note from Fig. 7.12 as compared to Fig. 7.7. First, the slopes of the landing position functions for regressive inter-word saccades were considerably smaller than for initial saccades into words. Second, data points for center-based mean landing site are clustered between 1 letter position right and/ or left of word center. Thus, launch site distance has not much of an effect on mean landing site. Basically, the SRE phenomenon with overshoots of word center in case of close launch site distances and undershoots in case of far distances is only present for 3-letter words.[54] Still, for a given word length the optimal center-based launch site distance was

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[54] In Fig. 7.12, landing sites left of word center represent an overshoot of word center while landing sites right of word center represent undershoot cases.

computed (Fig. 7.12). This hypothetical measure is further away from word center for longer compared to shorter words, a result which is due to the somewhat surprising finding that the overshoot tendency appears to be stronger for longer words.

In sum, by contrasting the highly systematic data for progressive inter-word saccades (Fig. 7.7) with the considerably less systematic data for regressive inter-word saccades (Fig. 7.12), it is concluded that for regressive inter-word saccades the SRE phenomenon is absent, or at least clearly attenuated.

Finally, the random placement error for regressive inter-word saccades was considered. The random error component is characterized by the standard deviation of landing position distributions. On the one hand, for progressive inter-word saccades a complex word length × launch site distance interaction was observed (Fig. 7.8). For regressive inter-word saccades, on the other hand, standard deviation increases as both word length and launch site distance increases (Fig. 7.13).

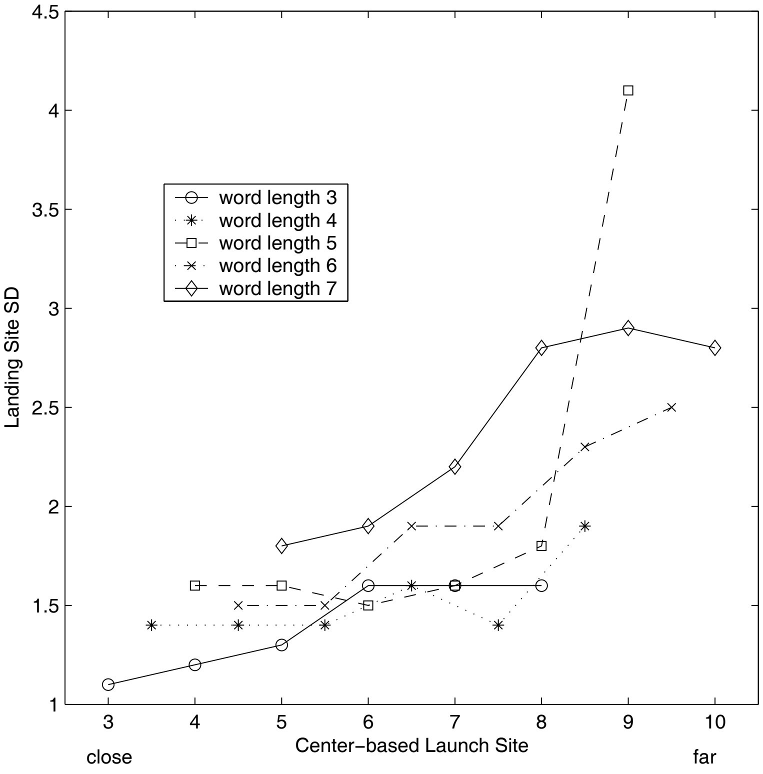

Fig. 7.13 Regressive saccades targeting 3- to 7-letter words. Estimated standard deviations of landing position distributions for different word lengths and launch sites, measured as distance from the center of the word.

7.3.3 Intra-Word Saccades (Refixations)

A refixation case consists of the initial saccade followed by a refixation ("1/multiple"), and the actual refixation saccade (e.g., "2/2"). There exist two research reports considering the influence of launch site on the initial saccade followed by a refixation (McDonald & Shillcock, 2004) and/or the actual refixation saccade (Radach & McConkie, 1998). In Sec. 4.3 (pp. 104) initial saccades in refixation cases were considered. The current analyses, however, focus on the refixation saccade following the initial saccade into a word. Again, the analyses relate to the current theoretical debate regarding the programming of intra-word saccades as opposed to inter-word saccades.

From the perspective of pre-programmed refixation saccades (cf., Sec. 3.4.1, pp. 78) it is argued that the programming of intra- and inter-word saccades is based on differing metrics (Vergilino-Perez & Beauvillain, 2004).[55] The authors argue that the planning of only one saccade directed to the word implies an initial landing position close to the word center to optimize word recognition within one fixation. This view is in line with the traditional view of word center being the target location for inter-word saccades. A different scenario is, however, pictured for refixation cases. As a consequence of (pre)planning a two-fixation sequence, the initial saccade is not directed toward the center of the word, but to a position near the word beginning (Vergilino-Perez *et al.*, 2004). The amplitude of the actual refixation saccade is then applied as a constant motor vector (Beauvillain *et al.*, 1999, 2000; Vergilino & Beauvillain, 2000, 2001; Vergilino-Perez & Beauvillain, 2004; Vergilino-Perez *et al.*, 2004). Basically, the "constant motor vector assumption" had to be rejected based on data from the reading with recurrent sentence shifts experiment (Sec. 3.4.3.2, pp. 92). Furthermore, the issue of differing metrics for intra- vs. inter-word saccades was carefully investigated by Radach & McConkie (1998), based on analyses of text reading data. They examined the influence of launch site distance on intra-word saccades (refixations) and inter-word saccades. Considering 9- to 11-letter words the authors showed that the landing position function continues smoothly from inter-word to intra-word progressive saccades with no discontinuity at the transition point between the two types of saccades. Interestingly, launch site also affected intra-word regressive saccades (refixations), but not – as replicated in Sec. 7.3.2 – inter-word regressive saccades. Thus, these analyses did not support the common distinction between intra- and inter-word progressive saccades.

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[55] Basically, single fixation cases and multiple-fixation cases are contrasted.

The metrics of intra-word saccades also comprises the question of a *target location* for the refixation saccade. In an influential paper, McConkie *et al.* (1988) put forth the idea that reading saccades have a functional target location which is the center of the word (Principle I, see Sec. 7.3.1.1, p. 182). There is now more or less consensus that this assumption is valid for progressive and regressive inter-word saccades. It is controversial, however, whether the assumption also holds for intra-word saccades, thus refixation saccades.

Radach & Heller (2000) understand refixation saccades as corrective movements directed towards the *word center* (see also Jacobs, 1987). Their argument is based on evidence from both fixation duration distributions (Radach, Heller, & Inhoff, 1999) and landing positions (Radach & McConkie, 1998). Most importantly, Radach & McConkie (1998) reported that both progressive and regressive refixations show the *saccadic range error* (SRE) phenomenon.

Within his strategy-tactics theory O'Regan (1990, 1992) sees refixations as the result of a specific "within-word tactic": When the eyes land at a non-optimal location at the word beginning or ending, a refixation is quickly executed that brings the eyes to the *opposite end* of the word (see also O'Regan & Lévy-Schoen, 1987).

A third prediction, at least for progressive refixations, can be derived from recent work by Beauvillain and colleagues on the pre-programming of refixation saccades. If two fixations are planned for a longer target word, the best way to ensure that all of the letters fall upon the fovea is to make the first fixation near the beginning and the second near the end of the word. Refixation saccade amplitude is believed to be applied as a pre-planned constant movement vector. Note that this assumption implies the *absence* of a specific target location for the refixation saccade.

Indeed, the most frequent refixation pattern is to fixate near the beginning of a word followed by a fixation near the end of the word (Rayner *et al.*, 1996). That does, however, not necessarily imply that these *realized* locations actually were the *intended* target locations within the word.

With the following analyses, the influence of launch site on progressive (Sec. 7.3.3.1) and regressive (Sec. 7.3.3.2) refixation saccades is examined in that landing position functions are computed. For a refixation saccade, the launch site is defined as the landing position of the initial saccade into the word. Thus, the range of possible launch sites is determined by word length. Supplementary, the first-against-second-position function is examined for words of different lengths (Sec. 7.3.3.3). Finally, conclusions with regard to saccade targeting are considered (Sec. 7.3.3.4).

7.3.3.1 Progressive intra-word saccades (refixations)

Previous analyses were devoted to the *launch site* of progressive refixations, showing that the great majority of these saccades are initiated from positions to the *left* of word center (Fig. 3.6a, p. 70). The current analyses were undertaken to investigate the landing site of progressive refixations as a function of launch site. In Fig. 7.14a, estimated mean landing site was plotted against launch site for 5-11 letter words. For each word length the relationship is linear: Mean landing site increases with launch site, thus demonstrating that the SRE phenomenon does exist for progressive refixation saccades. Interestingly, the slopes of the fitted linear regression functions, reflecting the magnitude of the SRE, increase with word length (Fig. 7.14a).

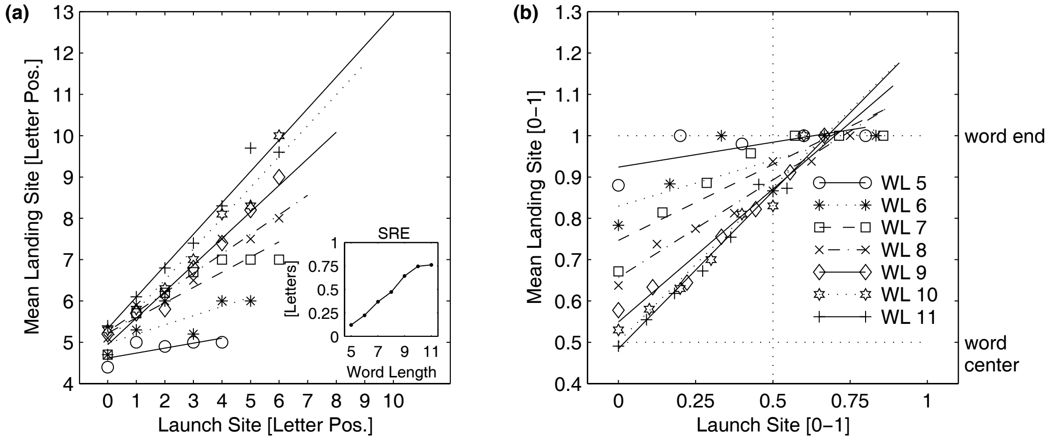

Fig. 7.14 Progressive refixation saccades within 5- to 11-letter words. Estimated means of landing site distributions a function of launch site distance, computed relative to the *beginning* of a word, for words of different lengths. Best fit linear curves are also presented for each word length. Panel (b) replots the data presented in panel (a), however, both launch site as well as mean landing site are now standardized for word length.

To further explore the SRE phenomenon for progressive refixations, data are replotted in Fig. 7.14b. Here, both launch site as well as mean landing site are now standardized for word length: For a given word length, values for both axes were divided by word length, leading to launch sites and mean landing sites ranging between 0 and 1 (cf., Sec. 3.1, pp. 62). On both axes, 0.5 thus marks the center of the word. Fig. 7.14b provides an explanation for the observed slope pattern. The last letter of a word is the right-most landing position for a saccade to qualify as a (progressive) refixation saccade. For shorter words, mean landing site is generally closer to the *end* of a word than for longer words (Fig. 7.14b). Consequently, for shorter words there is a restricted range for mean landing site to move as a function of launch site, resulting in a smaller slope of the landing position function (see also Sec. 7.3.3.3, Fig. 7.17).

Furthermore, as for the "random placement error", independent effects of both word length and launch site distance were observed. First, the standard deviation increased with word length. Second, the further the launch site moves off the word *beginning*, the smaller is the standard deviation of the refixation landing position distribution. The latter result is due to logical reasons: With increasing launch site, the range of potential landing positions is consistently restricted.

7.3.3.2 Regressive intra-word saccades (refixations)

Next, landing site of regressive refixations is examined as a function of launch site. Recall that refixation launch site is equivalent to the landing position of the prior initial fixation. In Fig. 7.15a, estimated mean landing site was plotted against launch site for 5-10 letter words. In this cases, launch sites are computed relative to the *end* of the fixated word. Launch sites are negative, -1 means that the eyes were launched from the final letter of the word. For each word length the relationship is linear: The further the launch site moves into the word, measured relative to the end of the word, the more the mean of the fitted refixation landing position distribution shifts to the left, thus towards the beginning of the word.

Thus, it is demonstrated that the SRE phenomenon also exists for regressive refixation saccades. Different from the results for progressive refixations, the slope of the fitted linear regression functions, reflecting the magnitude of the SRE, is constant across all word lengths tested (Fig. 7.15a).

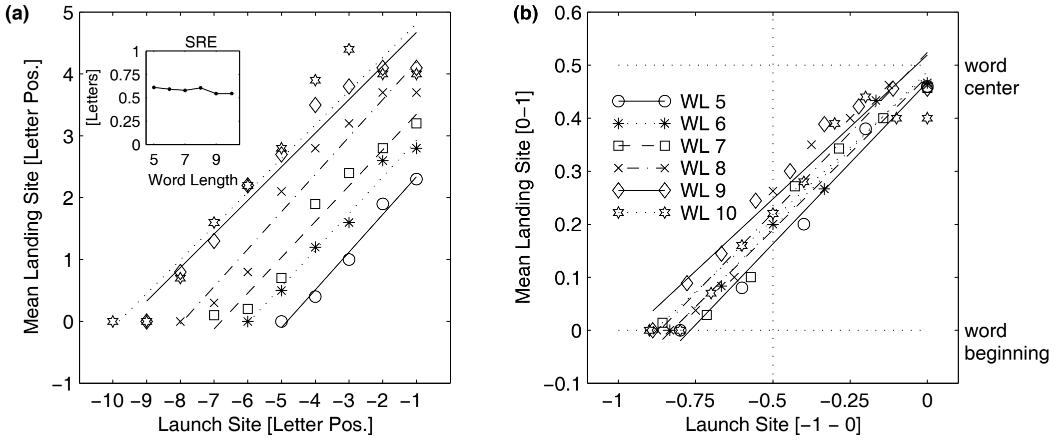

Fig. 7.15 Regressive refixation saccades within 5- to 10-letter words. Estimated means of landing site distributions a function of launch site distance, computed relative to the *end* of a word, for words of different lengths. Best fit linear curves are also presented for each word length. Panel (b) replots the data presented in panel (a), however, both launch site as well as mean landing site are now standardized for word length.

Furthermore, as for the "random placement error", independent effects of both word length and launch site distance were observed. First, the standard deviation increased with word length. Second, the further the launch site moves off the *end* of the word, the smaller is the standard deviation of the refixation landing position distribution which is, again, due to logical reasons.

7.3.3.3 Landing position of the refixation saccade as a function of initial landing position

In a final analysis, it was opted for a different way of data presentation which (1) allowed a direct comparison with refixation data obtained by Beauvillain and colleagues, and (2) provided complementary information to analyses presented in the two previous sub-sections.

Beauvillain and colleagues usually plot second fixation positions as a function of first fixation positions (e.g., Beauvillain *et al.*, 2000, Fig. 3; Vergilino-Perez *et al.*, 2004, Fig. 5). The same was done for all two-fixation cases produced by our 245 readers (Fig. 7.16). At a technical level, letter position was computed as continuous variable. For example, for 6-letter words values between 1 and 1.99 represent saccades that landed on the first letter of the word while values between 6 and 6.99 represent saccades that landed on the last letter of the word. Note that in an integer notation, "0" designates the space in front of the word. In the continuous notation, the space sign is thus represented with values between 0 and 0.99. For all analyses reported in this work, saccades that moved the eyes for at least one letter were considered (thus excluding microsaccades). Therefore, in case of a forward refixation saccade, minimum continuous second fixation position is 1 while maximum continuous first position equals word length (see upper diagonal in each panel of Fig. 7.16). As for backward refixations, minimum continuous first fixation position is 1 while maximum continuous second position equals word length (see lower diagonal in each panel of Fig. 7.16).

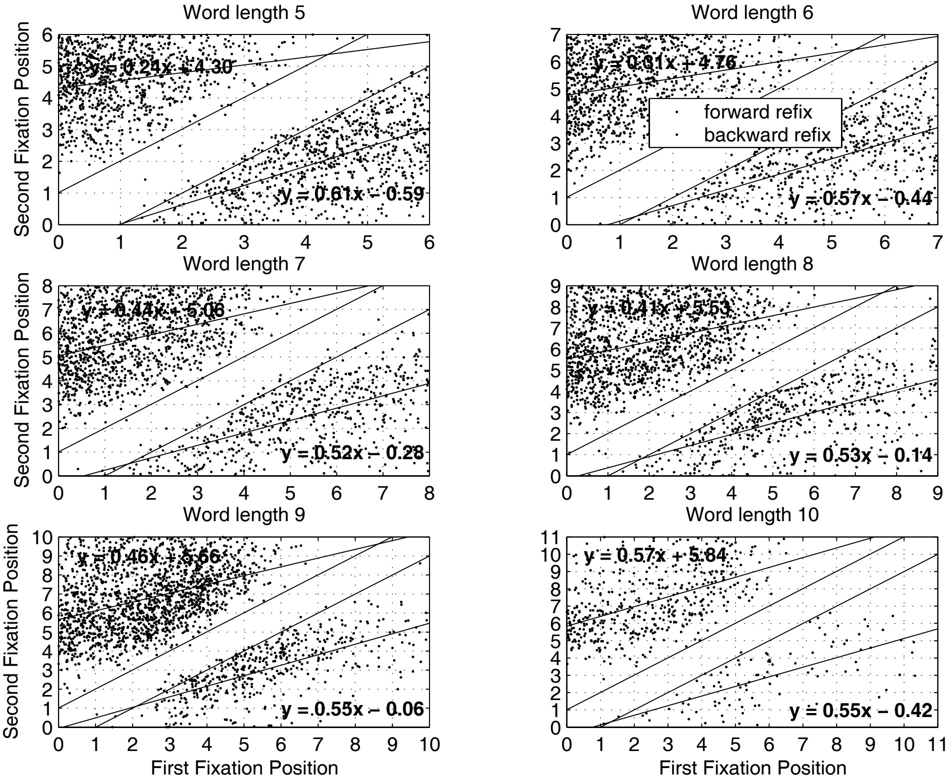

Fig. 7.16 Second fixation position as a function of first fixation position for refixation saccades on 5- to 10-letter words. Upper left triangle: forward refixations, lower right triangle: backward refixations.

Data representation in Fig. 7.16 reveals that regressive refixation saccades (which are never considered by Beauvillain and colleagues) show a linear relationship between first and second fixation position, at least for longer words. The slope of the fitted linear regression function is very similar for all word lengths tested, averaging 0.59 (range: 0.56-0.62). For progressive refixations, however, this linear relationship is less obvious. Slopes increase with word length, from 0.23 for 5-letter words to 0.59 for 10-letter words.

Basically, the current analyses lend support to the analyses presented in the two previous sections. The fitted linear regression functions presented in Fig. 7.16 are not the same as the landing position functions displayed in Fig. 7.14 (progressive refixations) & Fig. 7.15 (regressive refixations). Essentially, they visualize similar if not to say the same information, but in a different way. On the one hand, for a given first fixation position (launch site) the landing position distributions for the second fixation are considered (Fig. 7.14 & Fig. 7.15). On the other hand, the landing positions for the first and second fixation, each plotted as a function of their own landing position, are jointly considered (Fig. 7.16 & Fig. 7.17). Thus, the current figures visualize the frequency of all possible first-and-second-fixation-position combinations. In that respect the current analyses add to the analyses on PVL and/ or SRE where distributions, i.e. relative frequencies, are considered.

As compared to analyses of forward refixations made in an isolated word recognition paradigm (Vergilino-Perez *et al.*, 2004, Fig. 5), the data from continuous reading show a considerably higher variability. One of the reasons contributing to this variability is that in continuous reading the launch site distance for the initial saccade into the word is variable. Recall that analyses on the OVP curve have shown that the OVP moves left-ward with increasing launch site distance; in addition, there is a vertical displacement of the OVP curve (Sec. 7.1, pp. 176). When words and/ or letter strings presented in isolation are investigated, however, the launch site distance for the initial saccade into the word is held constant.

Actually, one might argue that the huge variability of data for progressive refixations does not allow to fit a linear regression function to the data. Therefore, for further analyses a 1 × 1 letter grid was superimposed on the data presented in Fig. 7.16 (see dotted horizontal and vertical lines). For each square (and/or triangle) of the grid, absolute frequencies of data points occurring in Fig. 7.16 were computed. Separately for forward and backward refixations, these frequencies were then converted to relative frequencies; thus, values sum up to 1. The resulting data are presented in a color plot (Fig. 7.17). Colors vary from black, through shades of gray[56], to white. Lighter colors represent higher relative frequencies (see color bar right of each panel). The coloring in Fig. 7.17 results from interpolation of the color of each cell of the grid at its four vertices.

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[56] In the original color plot, colors vary from black, through shades of red, orange, and yellow, to white.

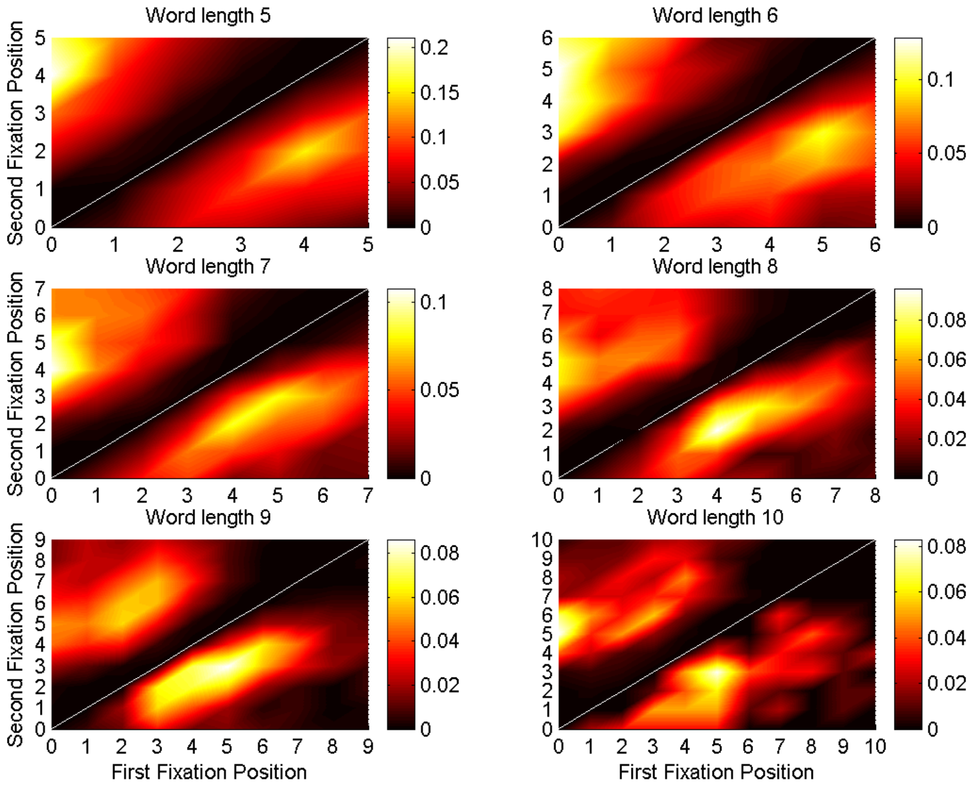

Fig. 7.17 Second fixation position as a function of first fixation position for refixation saccades on 5- to 10-letter words. Color plot for relative frequencies. Upper left triangle: forward refixations, lower right triangle: backward refixations.

The data representation in Fig. 7.17 supports the finding of a linear relationship between first and second fixation position for regressive refixations. Also, it sheds more light on the characteristics of progressive refixations. For progressive refixation saccades within 5- and 6-letter words, refixations strongly cluster at the very end of the word. This suggests that in case of rather short words, there must exist quite a few failed forward refixations, i.e. saccades that were intended to land on the currently fixated word but in execution landed on the next word (cf., case V in Fig. 6.2, p. 145). This empirical observation is consistent with SWIFT simulations which also related failed forward refixations to shorter words (Fig. 6.9b, p. 159). In analogy to the algorithm suggested in Sec. 6.1.2 (pp. 143), the proportion of failed forward refixations can be estimated from empirical data, based on extrapolations of landing position distributions (Fig. 5.3b, p. 127) beyond the right word boundary. Likewise, for longer words a proportion of forward refixations was actually intended to land on the next word (unintended forward refixation); for results obtained for simulated data see Fig. 6.9a, p.

159. For SWIFT-based estimations on the prevalence of these cases of mislocated fixations it is referred to Table 6.3 (p. 158).

7.3.3.4 Discussion

In the following, conclusions with regard to saccade targeting are considered. The considerations are based on the parameters (slope, intercept) of the landing position function and/or the first-against-second-position function, both represented by a fitted linear regression function. Two hypotheses are of special interest. If there was a perfect relationship between mean launch site and mean landing site (i.e., slope = 1) it would indicate that in case of a refixation the eyes are simply sent a particular distance further into the word (e.g., Vergilino & Beauvillain, 2000; but also McConkie *et al.*, 1988, with a similar rationale related to progressive inter-word saccades). Indeed, Beauvillain and colleagues consistently found a slope close to one which they interpret as evidence for the refixation saccade being coded as a motor vector of fixed amplitude applied irrespective of the first fixation position within the word (e.g., Vergilino-Perez *et al.*, 2004). Note that their results were obtained for isolated letter strings and/or words. The employed paradigms created a rather static and very repetitive situation with only long letter strings and/or words in the periphery while natural reading is representative of a dynamic and less predictable situation. Interestingly, for a continuous reading situation the "constant movement vector assumption" had to be rejected based on experimental data (Sec. 3.4.3.2, pp. 92) as well as corpus analyses presented above.[57] Namely, the current data yielded slopes smaller than one, on average they were around 0.5. More precisely, for regressive refixation saccades slopes around 0.6 were observed while slopes for progressive refixation saccades showed considerably variability and increased with word length. The interesting question to raise is what these results teach us in terms of a possible target location for the refixation saccade. Finding a slope of 0.5 would indicate that the eyes aimed for the center of gravity of the spatial configuration between the first fixation position and the end of the word (e.g., Vergilino-Perez *et al.*, 2004) and/ or the center of the word (cf., McConkie *et al.*, 1988).

First, it should be noted that there is a certain amount of progressive refixations which is launched right of word center. Thus, there exists a sub-population of

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[57] Interestingly, the constant movement vector assumption was not implemented in the SERIF model when estimating the proportion of pre-planned refixations in continuous reading (McDonald & Vergilino-Perez, 2006), nor was it tested with analyses of corpus data (McDonald & Shillcock, 2004).

refixations that obviously do not aim for the center of the word. The great majority of progressive refixations, however, is launched left of word center (Fig. 7.14; see also Fig. 3.6a, p. 70; Fig. 5.3a, p. 127) so that one could assume that they were aimed at the center of the word to be refixated. As far as landing position is concerned, for most word length × launch site combinations, mean landing site is clearly right of word center. Thus, it could be that the eyes aim for a specific location which would be the center of word or the center of gravity between the first fixation position and the end of the word. The eyes frequently overshoot (and sometimes undershoot) that target location due to oculomotor constraints (see also discussion in Sec. 7.3.4).[58] This view has actually been implemented in the SWIFT model (Engbert *et al.*, 2005). There, the "target the center of the word" strategy was implemented for all types of saccades, thus also for refixation saccades. Consequently, the strength of the SRE as well as a – somewhat hypothetical – optimal center-based launch site distance were derived from the data presented in Fig. 7.14a & Fig. 7.15a.

What is noteworthy from the empirical data, however, is that the overshoot tendency is less strong for regressive refixations (see also discussion in Sec. 7.3.4). Therefore, results for regressive refixations (Fig. 7.15) seem to be more in line with the notion of word center and/or center of gravity as the target location for the refixation saccade than results for progressive refixations. Recall, however, that there is quite a big proportion of regressive refixations launched left of word center as well as a certain amount of progressive refixations launched right of word center. In these refixation cases, word center is not a plausible candidate for a possible target location. Therefore, it might be more appropriate to assume that refixations target the center location between the first fixation position and the end of the word, rather than the center of word.[59]

In sum, the current analyses do not lend support to the "constant movement vector assumption" as suggested by Beauvillain and colleagues. Alternatively, it had been suggested that refixation saccades, as inter-word saccades, target the center of the word (Radach & McConkie, 1998). In principle, the current data are compatible with

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[58] Refixation saccade amplitude reflects the distance that is covered by the eyes while they move from first to second position within the word. Refixation amplitude is on average smaller than the amplitude of inter-word saccades. Likewise, because of both empirical and logical reasons center-based launch site distance is on average smaller in refixation cases than for inter-word saccades. Consequently, the eyes predominantly overshoot the center of the word.

[59] Note, however, that numerical landing position predictions derived for both assumptions tend to be very similar, since first fixation positions for refixations are located towards the beginning and/or end of words (Nuthmann *et al.*, in prep.).

that notion but the evidence is not very clear. In particular for progressive refixations, the data showed quite a bit of variability. It was suggested that it might be more appropriate to consider the center location between the first fixation position and the end and/or beginning of the word as the target location of refixation saccades. Further research is required to investigate the metrics of refixation saccades as well the differences between progressive and regressive refixation saccades.

7.3.4 Summary and Discussion

Summary of analyses for progressive inter-word saccades. Based on analyses of initial saccades into words, McConkie *et al.* (1988) explicated a set of basic visuomotor principles that can account for variations of landing positions within words. Sec. 7.3.1 (pp. 182) was devoted to replicate the underlying analyses for a comprehensive set of German reading data. Empirical landing position distributions, calculated as a function of word length and launch site distance, are well described by the normal distribution which is characterized by its mean and standard deviation. Consequently, the influence of launch site distance on the mean (Sec. 7.3.1.1.1, pp. 183) and standard deviation (Sec. 7.3.1.1.2, pp. 188) of Gaussian landing position distributions was investigated.

First, McConkie *et al.*'s (1988) empirical findings on the linear landing position function were replicated (Sec. 7.3.1.1.1, pp. 183). The main difference was that the optimal center-based launch site distance was about 5.4 letters to the left of word center whereas McConkie *et al.* reported 6 to 7 letters for English data. Second, McConkie *et al.* (1988) had found that landing site standard deviation was not influenced by prior fixation duration while mean landing sites converged toward a point slightly to the left of word center (Principle III). The current data, however, suggest that variance in landing position distributions is reduced following longer fixations while mean landing site does not systematically vary with prior fixation duration (Sec. 7.3.1.1.3, pp. 189). Third, McConkie *et al.* (1988) reported a non-linear increase of landing site standard deviation with increasing launch site distance with no additional effect of word length. For the current data, however, a rather complex word length × launch site distance interaction was observed (Sec. 7.3.1.1.2, p. 188).

Explanations for the landing position function: saccadic range error vs. global effect. The interesting question to raise is what these patterns of empirical results reveal about eye-movement control in reading. In this respect, the key finding is certainly the linear landing position function: With increasing launch site distance mean landing site systematically shifts to the left. From the fact that word length has a negligible effect on the center-based landing position function (see Fig. 7.7, p. 187), it is inferred that word center is the functional target location for progressive inter-word saccades in reading (McConkie *et al.*, 1988). There is, however, some deviation in directing the eyes to that target location. Here, the theoretical debate originates. The deviation is explained either in terms of a saccadic range error (McConkie *et al.*, 1988) or in terms of a global effect (Vitu, 1991a, 1991b).

According to McConkie *et al.*, the deviation is due to a motor error which has a systematic and a random component. The random error component is characterized by the standard deviation of landing position distributions. The systematic error component is reflected in the means of landing position distributions, i.e. the linear landing position function. The systematic error component is interpreted as a (saccadic) range error and thus a basic (oculo)motor phenomenon (McConkie *et al.*, 1988, referring to Kapoula, 1985; Poulton, 1981). On the one hand, oculomotor studies suggested that saccadic eye movements tend to undershoot the target (Henson, 1979) typically by about 10% of the total distance (Becker, 1972). On the other hand, there exists a range effect as a fundamental characteristic of motor skills (Poulton, 1974). The range effect has been investigated and verified in, for example, manual tracking tasks: Small distances are overestimated while large distances are underestimated. This led Poulton (1981) to suggest that such a response bias should also apply to saccadic movements. Indeed, using basic oculomotor tasks Kapoula (1985; Kapoula & Robinson, 1986) demonstrated that, at least under some circumstances, saccades also show a range effect in that the range of stimulus eccentricities in a block of trials influences the accuracy of the saccades. Subjects had to saccade to single targets in the periphery. The eyes moved accurately to a target at the middle of the range, overshot the closer targets and undershot targets that were further away. Kapoula's experiments support the view that saccades normally undershoot their target.[60] However, the existence of a saccadic range effect as such demonstrates that, contrary to the common belief in oculomotor physiology, saccades do not always undershoot their target. It has been demonstrated that the point at which an accurate mean saccade length is obtained (i.e. the point at which overshoots and undershoots are equal) varies with the lengths of saccades being executed within the task (Kapoula & Robinson, 1986). Thus, the range of saccade lengths required in the task determines the point of equality. One could say that

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[60] This undershoot propensity also exists in continuous reading.

participants tune their oculomotor behavior for maximum performance under the constraints of the visual system and the circumstances of a given oculomotor task. As for reading, McConkie *et al.* (1988) computed an optimal center-based launch site distance of 6-7 letters which was slightly below the median saccade length for their data set. Interestingly, for the current data set an optimal distance of 5.4 letters was computed which is very close to the mean word length for the Potsdam Sentence Corpus (5.5 letters).[61]

While the saccadic range error explanation is widely accepted, it should be noted that alternative explanations have been put forth. In particular, it has been suggested that the center of gravity of the visual configuration influences the initial fixation location. The so-called "global effect" has been first observed and examined in basic oculomotor tasks (e.g., Findlay, 1982). The term "global processing" refers to the idea that the information being used in the calculation of saccade amplitude is obtained by integrating information across a relatively large spatial window (Findlay, 1982). Numerous oculomotor studies have shown that a saccade towards a peripheral target is deviated from its goal by the presence of other stimuli (distractors) in the peripheral visual field. When the eye saccades to a group of eccentric targets, it tends to land in a position which can be loosely described as the center of gravity of the visual configuration, a finding which has been termed as "global effect". For example, Coëffé & O'Regan (1987) employed a task where participants had to saccade to letter targets within 9-letter strings. When the eye was aiming for the eighth letter, it landed short of it, but when it was aiming for the second letter, it overshot it. It is noteworthy that the eccentricity of letter strings had no effect which argues against a range error explanation. The results were interpreted in terms of a global effect. The effect is not seen as a motor, but rather as a perceptual phenomenon which is due to inaccurate spatial localization of the target. In a similar manner, Vitu investigated the existence of a global effect in reading-like situations (Vitu, 1991a, 1991b). As McConkie and colleagues, Vitu (1991b) assumed that a word is selected as the target for the next saccade while the OVP and/or center of word is the specific target location within that word (but see Vitu, 2003). The eyes are deviated from this goal "by the position of the cortically weighted center of gravity of the defined critical peripheral configuration" (Vitu, 1991b, p. 1312). Radach & McConkie (1998) argued, however, that the center of gravity within an attended region cannot account for the linear center-based landing

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[61] Median saccade length for initial saccade into words is 7.16 letters.

position function which is characterized by a strong effect of center-based launch site distance but only a very small effect of word length.

What is interesting about these two explanations is that they operate with two distinct theoretical concepts. On the one hand, the finding that mean landing site is systematically influenced by launch site distance is understood as the manifestation of a basic principle of controlled muscle movement, realized in the form of a saccadic range error (McConkie *et al.*, 1988). Thus, the empirical phenomenon is interpreted as being a basic (oculo)motor phenomenon. On the other hand, according to the center-of-gravity notion, perceptual and visuomotor components are predominantly contributing to the phenomenon. In perspective, it would be desirable to contrast the two explanations by employing appropriate experimental paradigms and/or simulations with a computational model. In that way it might be possible to separate the oculomotor vs. perceptual parts of both explanations.

Regressive inter-word saccades. The two error components, systematic and random, were also examined for regressive inter-word saccades (Sec. 7.3.2, pp. 192). Interestingly, regressive inter-word saccades show different landing position characteristics than do progressive inter-word saccades and refixation saccades. Launch site distance had no systematic effect on mean landing site, and the saccadic range effect was virtually absent. Rather, the eyes go consistently, with some random error producing the Gaussian shape of the observed landing position distributions, to their target word. One might argue that if the saccadic range error was a general phenomenon of saccadic control in reading, it should also emerge for regressive inter-word saccades. It has been shown, however, that neither the undershoot propensity of the saccadic system (Kapoula & Robinson, 1986) nor the global effect (Coëffé & O'Regan, 1987) are inevitable. In case of a inter-word regression, the spatial coordinates of the target word might have been already coded in spatial memory during the initial encounter with the word, and the oculomotor system might be able to use that information when regressing back to the selected word. Interestingly, intra-word regressive saccades (refixations) do not show these unusual characteristics. Further research is needed to understand the special role of regressive inter-word saccades.

Refixations. Radach & McConkie (1998) showed that the landing position function continues smoothly from inter-word to intra-word progressive saccades with no discontinuity at the transition point between the two types of saccades. Note, however, that the authors considered very long words only (9 to 11 letters) while the current analyses were based on word lengths 5 to 10 for progressive refixations and word lengths 4 to 8 for progressive inter-word saccades. The current data more or less replicated Radach & McConkie's findings for refixations (Sec. 7.3.3, pp. 196). Launch site had a systematic effect on mean landing site for regressive refixations. For progressive refixations within short words, however, a pronounced overshoot was observed which was reflected in an attenuated SRE (Fig. 7.14, p. 198).

In post hoc analyses, word length and initial landing position influence whether a given saccade qualifies as an intra-word or inter-word saccade. Furthermore, saccades can be misguided, leading to unintended refixations and/or failed refixations. It is therefore assumed that, at least in case of progressive saccades, the oculomotor system does not explicitly distinguish between inter-word and intra-word saccades. The saccadic range error phenomenon was related to a performance tuning notion (see above). The performance tuning, which would be optimized for progressive inter-word saccades as the default in reading, would lead to frequent overshoots of word center in case of progressive refixations.

In sum, the current analyses do not support the common distinction between intra- and inter-word progressive saccades. Rather, a distinction between progressive and regressive saccades seems to be more appropriate (cf., Radach & McConkie, 1998).

8 Influence of Word Frequency

While word length and launch site distance are the most important "low level" visuomotor variables influencing measures of eye-movement control in reading, word frequency is the most important "higher level" cognitive variable. Among cognitive theories of eye-movement control in reading, in particular the E-Z Reader model emphasizes the role of word frequency in word identification and triggering of saccades (Reichle *et al.*, 2003). The following analyses were undertaken to examine the influence of word frequency on PVL (Sec. 8.1), OVP (Sec. 8.3) and the Fixation-Duration IOVP effect (Sec. 8.2). More precisely, an orthogonal data sampling by word length and word frequency was employed.

8.1 Preferred Viewing Location

There is ample empirical evidence that cognition affects the selection of the next saccade target word. As for computational modeling, in the SWIFT model (Engbert *et al.*, 2005) saccade target selection is due to a competition among words with different activations from a dynamically changing activation field. The maximum activation of a word is related to the word's processing difficulty which depends on printed word frequency (per million words) and predictability.

There is controversial evidence as to whether cognition also influences where the eyes land within that selected word. Analyses of text reading data from four German adults showed no effect of orthography on initial landing position within words (Radach & Kempe, 1993; Radach & McConkie, 1998). However, Vonk, Radach, & van Rijn (2000) suggested that text reading studies might have failed to find landing position effects because they induce a "risky" reading strategy compared to the careful reading strategy induced by single sentence reading. Furthermore, these studies have been criticized for not using strong manipulations of orthographic regularity (Hyönä, 1995).

Only recently, a dissertation project was devoted to linguistic influences on landing position (White, 2003). The experiments used single line sentences with embedded critical target words. It was shown that orthographic familiarity and regularity influence landing positions (e.g., White & Liversedge, 2004).

In the original reading experiment (Exp. 1), 245 participants read the 144 sentences of the Potsdam Sentence Corpus, one at a time. It was opted for an analysis scheme that would generate a sufficient number of data points to allow statistical analyses. Therefore, the analysis was based on *all* corpus words which were categorized as high- vs. low-frequency words based on a median split of CELEX Frequency Norms (Baayen *et al.*, 1993) that were available for all corpus words. Furthermore, to ensure stable participant-based PVL curves showing the characteristic Gaussian shape, computations were based on *all* reading fixations (Fig. 8.1).[62] However, given the high negative correlation between word frequency and word length (-.64 for 994 corpus words, i.e., excluding the first word of each sentence) the orthogonal data sampling yielded a highly uneven number of cases for fixations on high- vs. low-frequency words per word length. For short words, fixations on high-frequency words are prevailing, while for long words the majority of fixations are associated with low-frequency words (see Fig. 8.1). For each participant and every word length × word frequency category tested, an empirical PVL curve was computed and then fitted to a normal curve. Statistical analyses were run on means and standard deviations of the best-fitting normal curves.

As for results, the data are indicative of a small but systematic effect of word frequency on the mean of the normal fitted landing position distributions (Table 8.1, Fig. 8.2).

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[62] Again, first and last fixations in a sentence as well as fixations being shorter than 30 ms and longer than 1000 ms were excluded.

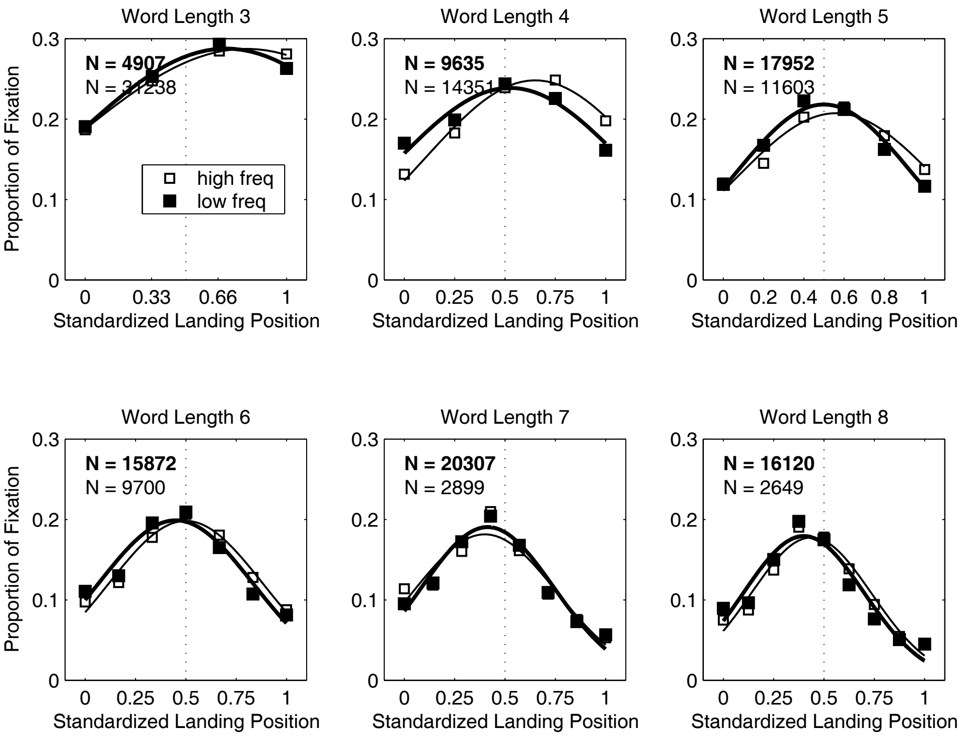

Fig. 8.1 Landing position distributions for high-frequency words (open squares) vs. low-frequency words (full squares) as a function of word length. Each panel represents data for a given word length (3 through 8). Also presented is the best-fitting normal curve for each distribution.

Table 8.1 Normal fit to word-length dependent landing position distributions for high-frequency words vs. low-frequency words: Estimates of parameters *M*, M_C, *M'* and *SD*.

WORD LENGTH	CENTER OF WORD	HIGH-FREQUENCY WORDS					LOW-FREQUENCY WORDS				
		M	M_C	*M'*	*SD*	χ^2	*M*	M_C	*M'*	*SD*	χ^2
3	2	2.14	0.14	0.71	2.18	0.00532	1.88	-0.12	0.63	1.85	0.01661
4	2.5	2.66	0.16	0.66	2.26	0.00951	2.15	-0.35	0.54	2.45	0.01196
5	3	2.95	-0.05	0.59	2.63	0.01274	2.55	-0.45	0.51	2.4	0.00872
6	3.5	3.19	-0.31	0.53	2.55	0.01623	2.79	-0.71	0.46	2.51	0.01056
7	4	2.82	-1.18	0.4	2.47	0.0491	3.02	-0.98	0.43	2.44	0.01011
8	4.5	3.5	-1	0.44	2.36	0.05912	3.19	-1.31	0.4	2.47	0.0135

Note. $M_C = M -$ Center of word. $M' = M/$ word length. χ^2 denotes sum of squared residuals.

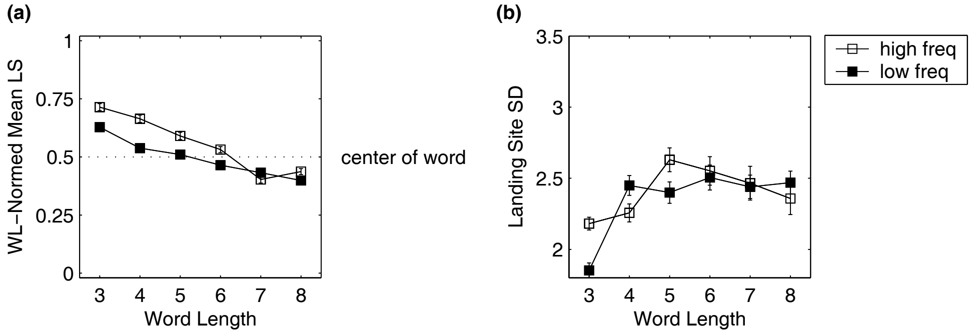

Fig. 8.2 Normal fit to landing position distributions for high-frequency words (full squares) vs. low-frequency words (open squares): *M'* (panel a) and *SD* (panel b) of the fitted normal curve as a function of word length.

For both *M'* and *SD*, in separate analyses, a 2 × 6 repeated measures ANOVA with "word frequency" and "word length" as within-subject factors was conducted.

In addition to the word length effect on *M'* [*F*(5,221) = 121.528, *p* = .000; cf., Sec. 4.1, pp. 100), there was also a significant main effect of word frequency on mean landing site: Readers landed further into the word when it was a high-frequency word as compared to low-frequency words [*F*(1,225) = 68.203, *p* = .000]. However, this was true for 3- to 6-letter words only [significant word frequency × word length interaction: *F*(5,221) = 10.216, *p* = .000]. As for the standard deviation of the fitted normal landing position distributions, there was no significant effect of word frequency [*F*(1,225) = 1.882, *p* = .171], but a word length effect [*F*(5,221) = 12.464, *p* = .000] that interacted with word frequency [*F*(5,221) = 4.371, *p* = .001].

8.2 Fixation-Duration IOVP Effect

In the current section it is investigated whether the Fixation-Duration IOVP effect is modulated by word frequency. In previous studies it was reported that the effect of word frequency on fixation durations was independent of landing position (Vitu *et al.*, 2001; see also Rayner *et al.*, 1996, but reporting a non-significant effect of landing position).

The current analyses will not follow the scheme established in Sec. 5.2 (pp. 132). There, all fixations on all corpus words were considered (see also Sec. 4.4, pp. 107), and participant-based empirical curves were fitted to a quadratic function. However, when data were further split by word frequency, participant-based curves frequently showed a poor goodness of fit (cf., Sec. 5.3, pp. 138, last paragraph). Therefore, a different analysis scheme was adopted for the current analyses. First, words of all lengths were divided into five zones (cf., Vitu *et al.*, 2001) so that data could be combined across different word lengths. Second, corpus target words were considered, i.e., one word per sentence constituting an orthogonal word length (3) × word frequency (2) design with 24 words in each cell. Third, only single fixations were considered (cf., Sec. 5.1.1, p. 124).

Fig. 8.3 depicts mean single fixation durations on target words of different lengths (a: 3 and 4, b: 5, 6, and 7, c: 8 and 9) and frequency (high: > 50 occurrences/million vs. low: 1 to 4 occurrences/million) as a function of the landing zone initially fixated. A Fixation-Duration IOVP effect was found for every word length × word frequency combination.

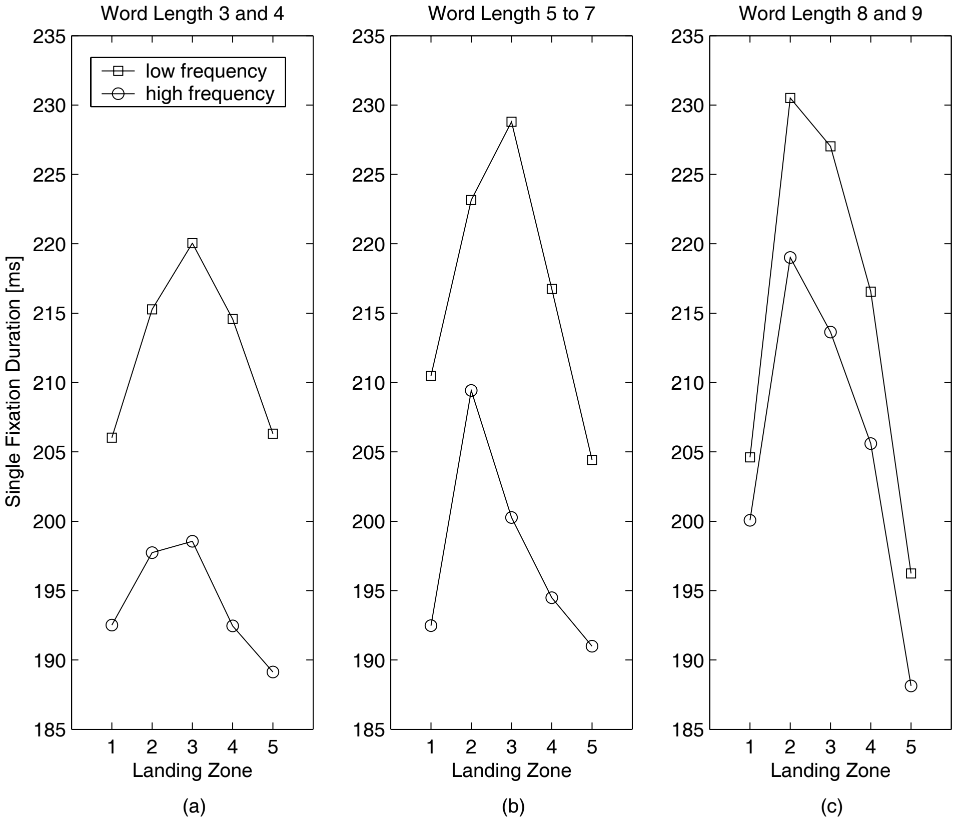

Fig. 8.3 Mean duration of single fixations on target words of different lengths (a: 3 and 4, b: 5-7, c: 8 and 9) and frequency (high vs. low) as a function of the landing zone initially fixated. Words of all lengths were divided into five zones, and data for each zone were averaged across word lengths and subjects.

As for statistics, a 2 (high vs. low frequency) × 3 (short vs. medium vs. long word length) × 5 (landing zones) repeated measures ANOVA was carried out. [63] First, single fixation durations increased with length [$F(1,2) = 14.925$, $MSE = 1755.388$, $p = .000$, $\eta^2 = .062$] and decreased with frequency [$F(1,1) = 196.975$, $MSE = 1799.497$, $p = .000$, $\eta^2 = .467$], see also Kliegl *et al.* (2004). The frequency effect decreased for longer words [$F(1,2) = 7.463$, $MSE = 1596.111$, $p = .001$, $\eta^2 = .032$ for the frequency × length interaction]. Note, however, if the same analysis was based on all corpus words, instead of target words only, the frequency effect increased for longer words [$F(1,2) = 10.266$, $MSE = 783.269$, $p = .000$, $\eta^2 = .044$]. Importantly for the present work, there was a significant main effect for landing zone [$F(1,4) = 45.403$, $MSE = 2405.892$, $p = .000$, $\eta^2 = .168$] reflecting the IOVP effect and a significant interaction of word length and landing zone [$F(1,8) = 9.960$, $MSE = 1830.017$, $p = .000$, $\eta^2 = .042$] with a stronger

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[63] For statistical analyses, 19 out of 245 participants were excluded because they had contributed less than 100 valid sentences to the data base, cf., Sec. 2.1.5, p. 21.

landing zone effect (= IOVP effect) for longer words. Finally, there was a marginally significant interaction of frequency and landing zone at the 5%-error level [$F(1,4) = 3.999$, $MSE = 1415.225$, $p = .003$, $\eta^2 = .017$]. In separate ANOVAs for each word length category, this interaction was never significant ($p > 0.05$) which is consistent with analyses by Vitu *et al.* (2001). Thus, it seems reasonable to conclude that single fixations on low frequency words were consistently longer than on high frequency words with this effect being largely independent of landing zone (Rayner *et al.*, 1996; Vitu *et al.*, 2001).[64]

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[64] In Nuthmann *et al.* (2005), a non-significant word frequency × landing zone interaction was reported [$F(1,4) = 2.196$, $p = .068$], based on analyses of data from 200 participants. In the current thesis, analyses are consistently based on data from 245 participants. For statistical analyses, 19 out of 245 participants were excluded because they had contributed less than 100 valid sentences to the data base, cf., Sec. 2.1.5, p. 21.

8.3 Optimal Viewing Position

Next, the influence of word frequency on the parameters of the quadratic refixation probability function is examined. The analyses presented in the current section are of theoretical relevance given that the programming of refixations is currently a topic of debate. In particular, parameter *B'* is in the spotlight of theoretical argumentation (see Sec. 8.3.2 below). As for parameter *A*, the vertical offset of the curve, the present analyses extend existing findings by McConkie *et al.* (1989).

To ensure a sufficient amount of data points, analyses were based on *all* words of the Potsdam Sentence Corpus rather than target words only. Since length and frequency of fixated words are correlated, the data were partitioned by word length and word frequency simultaneously, and word refixation curves were examined for the resulting cells (cf., Table 8.2).

Table 8.2 Analysis of refixation probability curves: six word lengths (3-8) × five word frequency classes. The cells of the design which were considered by McConkie *et al.* (1989) are indicated with "×" signs. Furthermore, the cells of the design which cannot be tested with the Potsdam Sentence Corpus data are indicated with "–" signs.

WORD FREQ. CLASS	**WORD LENGTH**					
	3	**4**	**5**	**6**	**7**	**8**
1				×		
2		×	×	×	×	
3				×		
4					–	–
5			–	–	–	–

For a given word frequency class, Fig. 8.4 presents word refixation probability curves for words of lengths 3 through 8. The empirical refixation probability curves were fitted to a quadratic function with three parameters (see Sec. 3.1, pp. 62). Fig. 8.5 plots the fit parameters as a function of word length. To facilitate a direct comparison with McConkie *et al.* (1989), the curves from Fig. 8.4 are replotted in Fig. 8.6, now with a different grouping: For a given word length, the figure depicts word refixation probability curves for word frequency classes 1 through 5. Likewise, Fig. 8.7 shows the same means as Fig. 8.5, but this time for a given word length as a function of word frequency.

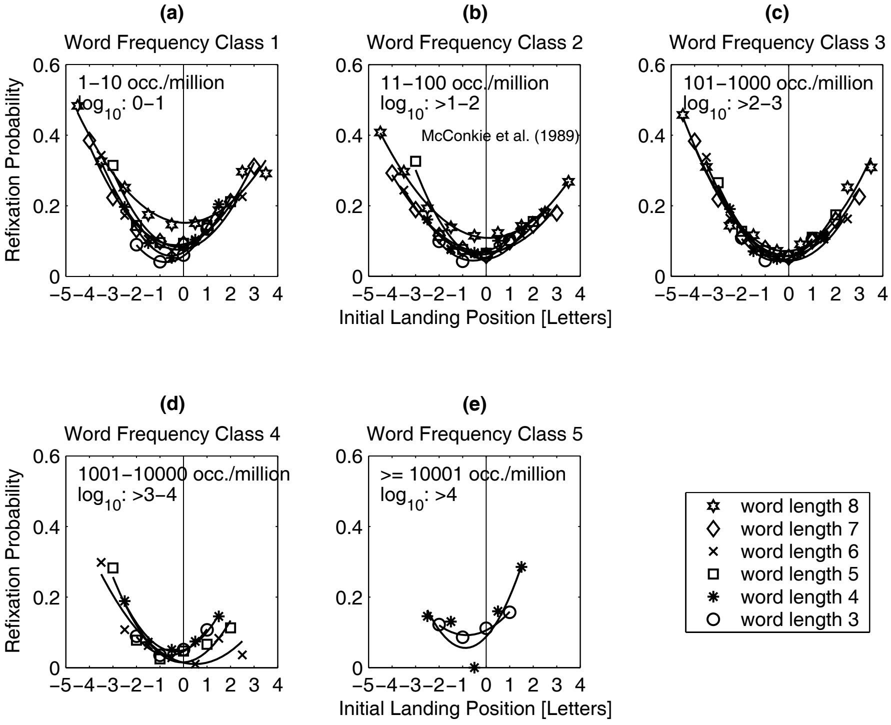

Fig. 8.4 Refixation probability curves with word frequency held constant. Each panel represents a given word frequency class and displays refixation probability curves for word lengths 3 through 8. Note that panel (b) represents the word frequency class examined by McConkie *et. al.* (1989), see their Fig. 6.

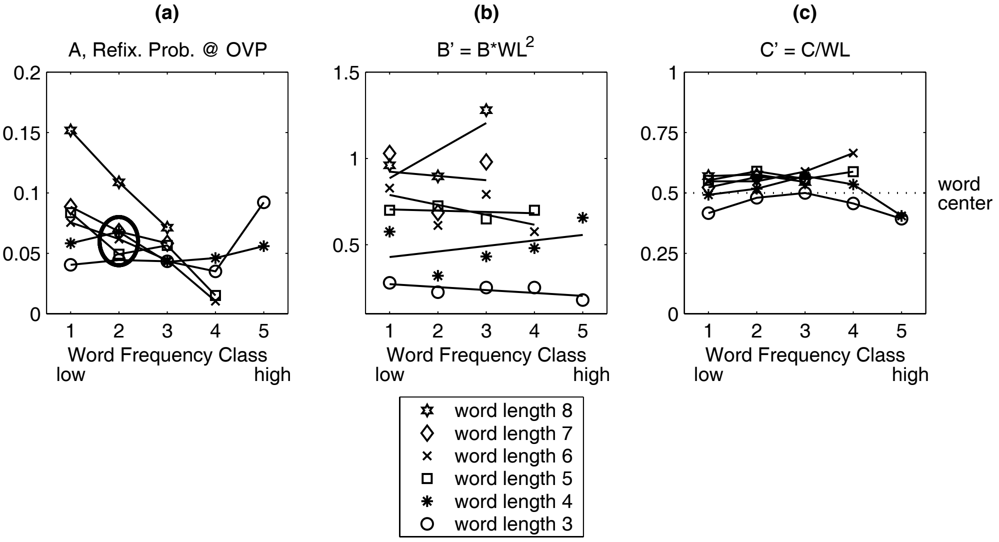

Fig. 8.5 Quadratic fit to refixation probability curves when word frequency is held constant: Parameters *A* (panel a), *B'* (panel b), and *C'* (panel c) as a function of word length. The ellipse in panel (a) marks the part of the word length × frequency design that was examined by McConkie *et al.* (1989), cf. Table 8.2.

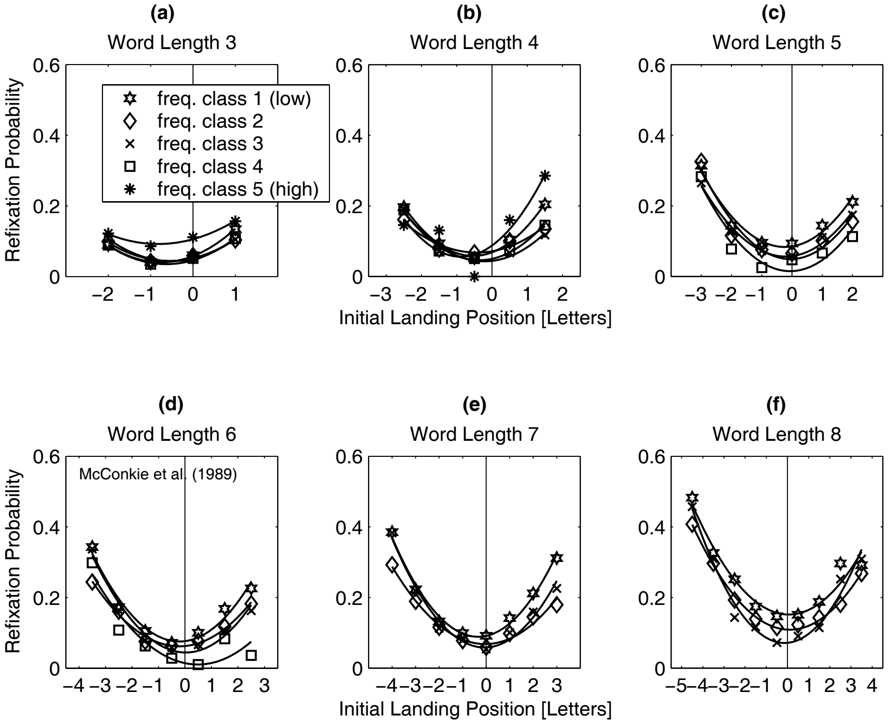

Fig. 8.6 Refixation probability curves with word length held constant. Each panel represents a given word length (3-8) and displays refixation probability curves for 5 word frequency classes. Note that panel (d) with data for word length 6 represents the word frequency class examined by McConkie *et. al.* (1989), see their Fig. 7.

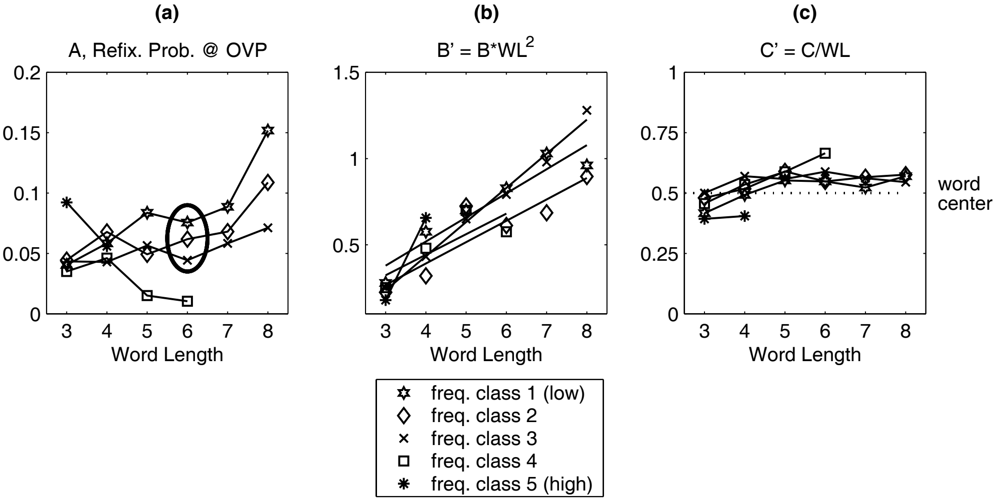

Fig. 8.7 Quadratic fit to refixation probability curves when word length is held constant: Parameters *A* (panel a), *B'* (panel b), and *C'* (panel c) as a function of word frequency. The ellipse in panel (a) marks the part of the word length × frequency design which was examined by McConkie *et al.* (1989), cf. Table 8.2.

8.3.1.1 Parameter *A*: Refixation probability at OVP

In an influential paper, McConkie *et al.* (1989) reported that the variation of parameter *A* is primarily due to differences in word *frequency* rather than differences in word *length*, though acknowledging that "this still requires closer examination with a larger data set" (p. 249) because their data set did not allow them to analyze the full word length × word frequency design (Table 8.2). The present large data set allowed to test whether McConkie *et al.'s* (1989) findings generalize to a broader word length × frequency band spectrum. For frequency classes 1 through 3, there was a sufficient number of data points for all six word lengths considered (3 through 8). Since the correlation between length and frequency is negative (−0.62 for 850 corpus words, i.e. excluding the first and last words of each sentence), the Potsdam Sentence Corpus did not provide us with enough fixations on long high-frequency words so that six cells of the design had to be excluded from analyses (Table 8.2).

It is important to note that McConkie *et al.* (1989) tested only a partial main effect of word length (see Table 8.2) when they report that "when word frequency is held constant, there is little (vertical) separation among the curves for words of different length" (p. 249). Their analysis was restricted to fixations on words with a log frequency of 1.0 to 1.9 (word frequency class 2). Interestingly, for this particular frequency band their observation of a lacking word length effect on parameter *A* is replicated for German data (ellipse in Fig. 8.5a, see also Fig. 8.4b). Furthermore, McConkie *et al.* (1989) tested and observed a partial main effect of word frequency by considering 6-letter words with varying word frequency (classes 1 through 3, see Table 8.2): When word length is held constant at six, there is a (vertical) separation among the curves for words of different word frequency bands. Again, this observation of a word frequency effect on parameter *A* is replicated for German data (ellipse in Fig. 8.7a, see also Fig. 8.6d). McConkie *et al.* (1989) concluded that the variation of parameter *A* is primarily due to differences in word *frequency* rather than differences in word *length*.

With the current analyses it is tested whether this finding generalizes to a broader word length × frequency band spectrum. On the one hand, we observe a word length effect on parameter *A* for words with lower frequency (1-3, most clearly for class 1)[65], but not for high frequency words (4-5) (Fig. 8.5a). On the other hand, there is a clear frequency effect for long words (5-8), but not for short words (3-4) (Fig. 8.7a). Thus, for *long* words we observe a *frequency* effect with higher *A* for low-frequency

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[65] This effect is mainly caused by adding word length 8 to the word length × word frequency design.

long words (or: for *low-frequency* words a word length effect with higher *A* for longer words is found). Taken the results for parameter *A* together, the findings are indicative of an interaction between word length and word frequency.

8.3.1.2 Parameter *B'*: The penalty paid for not fixating at OVP

McConkie *et al.* (1989) argued "As the initial landing position moves away from the center of the word, thereby reducing the amount of clear visual information provided by the word, the influence of word frequency should become greater" (p. 251). Thus, not only a word frequency effect on parameter *A* was predicted, but also an additive word frequency effect on parameter *B'* with a lower slope parameter for higher frequency words.

However, there was no effect of word frequency on the slope of the refixation probability curve (McConkie *et al.*, 1989). While McConkie *et al.* reported this finding for text reading data, it was also found in isolated word recognition studies (Vitu, 1991c). Only recently, Vergilino-Perez *et al.* (2004) reported a main effect of word frequency that did not interact with landing position.[66] Thus, refixation probability for low frequency words was consistently higher than for high frequency words with this effect being independent of initial landing position.

What do data from reading the Potsdam Sentence Corpus show us? If anything, word frequency has a very small effect on parameter *B'* (Fig. 8.7b). Furthermore, as has been shown previously (Sec. 3.1, Fig. 3.2c, p. 62), the data replicate a main effect of word length on parameter *B'* (Fig. 8.5b) with a higher "penalty" of fixating at a sub-optimal position for longer words. In addition, there is no word frequency × word length interaction.

8.3.1.3 Parameter *C'*: Optimal viewing position

As for parameter *C'*, the data are indicative of a small word length effect (Fig. 8.5c), but no frequency effect (Fig. 8.7c).

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[66] A different analysis scheme was, however, adopted. Rather than investigating the parameters of the quadratic refixation probability function, a word frequency ×·word length × landing zone design was tested. Furthermore, the obtained refixation curves did not show the typical quadratic shape (Vergilino-Perez *et al.*, 2004, Fig. 3) because with the employed paradigm only progressive refixations were elicited.

8.3.2 Discussion

In Sec. 8.3, the influence of both word length and word frequency on the parameters of the quadratic refixation probability function was examined.

Parameter A: refixation probability at OVP, vertical offset of the curve. For analyses, refixation probability data can be split by either word length or word frequency. It was shown that both variables influence parameter *A* of the refixation probability curve (McConkie *et al.*, 1989). Estimating the unique contribution of both variables, which are negatively correlated, requires orthogonal data sampling. Note that McConkie *et al.* (1989) investigated partial main effects (cf., Table 8.2). Analyses of the current data set did replicate their findings, but extended the analyses in that word length × word frequency interactions were considered. McConkie *et al.* concluded that the variation of parameter *A* is primarily due to differences in word frequency rather than differences in word length (1989). Analyses of the current data set, however, challenge that conclusion in showing that the data pattern is more complex. Roughly, the frequency effect is stronger for longer words and/or the word length effect is stronger for low-frequency words.

Parameter B: penalty for not fixating at OVP, slope of the curve. The current data suggested that there is a strong effect of word length on parameter *B’* whereas the effect of word frequency is negligible.

McConkie *et al.* (1989) suggested that the *B* parameter indicates the rate of drop-off of visual information necessary for reading as a function of retinal eccentricity.

Effect of word length. Based on the results of the current analyses, it is suggested that the effect of word length on *B’* can be linked to the population of corrective refixation saccades due to a sub-optimal initial landing position. The penalty for landing at either end of a word, instead of at landing at OVP, is higher for long compared to short words, because for long words there is a higher eccentricity from OVP.

Effect of word frequency. It is somewhat surprising that there is no effect of word frequency on *B*, the parameter of the refixation probability curve which is currently in the spotlight of a theoretical debate on the programming of refixation saccades. Namely, Vergilino-Perez *et al.* (2004) interpreted the lacking effect of word frequency on the slope of the refixation curve as an argument in favor of their pre-programming hypothesis of refixation and thus against the assumption that the decision to refixate is made during the first fixation on the word (see Sec. 3.4.1, pp. 78, for the rational underlying the pre-programming hypothesis as opposed to the direct-control hypothesis). More precisely, with their argumentation Vergilino-Perez *et al.* (2004) relied on two findings. First, there is a left-ward shift in initial landing position distributions in refixation cases as compared to single-fixation cases. Second, refixation probability is affected by word frequency while this main effect does not interact with landing position. They concluded that the decision to refixate is not made during the first fixation. Rather, most refixation saccades are preplanned – on the basis of the parafoveal word length – and are sometimes cancelled in case of successful lexical processing during the first fixation on a high-frequency word.

However, a lacking word frequency effect on parameter *B* is compatible with both the pre-programming hypothesis as well as the direct-control hypothesis of refixation programming. From the direct-control perspective, one could argue that a certain population of refixations is triggered by negative feedback about the progress of early word processing, with this occurring more often for low-frequency than for high-frequency words. At any rate, it is not at all clear, why the direct-control hypothesis would necessarily predict a word frequency effect on *B'*, the (transformed) slope of the quadratic function. Interestingly, Radach & McConkie (1998) found that saccades launched from the initial fixation within lower-frequency words have a smaller amplitude as compared to saccades launched from higher-frequency words. Consequently, for low-frequency words, more intra-word saccades (refixations) than inter-word saccades are launched from the initial landing position. Word frequency thus influences how many of the saccades remain on the current word vs. go to the next. For the saccade amplitude effect, word frequency does not interact with initial landing position. Therefore, the effect of word frequency on the word refixation probability curve is basically restricted to a vertical displacement of the curve.

In sum, it appears that word identification, as reflected in the frequency of occurrence of the (re)fixated word in a given language, can both cancel a pre-programmed refixation saccade program as well as ad hoc initiate a refixation saccade program.

Parameter C: OVP, horizontal offset of the curve. There is no strong and systematic influence of neither word length nor word frequency on parameter *C*, reflecting the OVP.

First and second fixation duration. The temporal aspect of refixation behavior is reflected by first and second fixation durations. Word-based statistics had revealed that there was a significant word frequency effect on first fixation duration in Experiments

3-5, but not in the mindless reading experiment (Exp. 2, see Table 2.2, p. 59). In none of the tested experimental manipulations, however, was there a significant effect of word frequency on the duration of the second fixation. This pattern of results suggests that the temporal aspect of the ad hoc decision to initiate a refixation and/or the decision to cancel a pre-planned refixation saccade program is influenced by word difficulty. The finding that second fixation duration is not influenced by word frequency anymore indicates that, in the majority of cases, word identification has been completed (relatively early) during this second fixation. Note that these findings are in conflict with results obtained by Beauvillain and colleagues. In a step paradigm, Beauvillain *et al.* (2000, Exp. 2) observed no frequency effect on first fixation duration in two-fixation cases while there was a significant frequency effect on second fixation duration. In an isolated word recognition paradigm, Vergilino-Perez *et al.* (2004) observed significant frequency effects for both the first and the second of two fixations on a word.

9 General Discussion

9.1 Fixation-Duration IOVP Effects in Continuous Reading

Much of the work in the present thesis was related to the IOVP effect, that is the counterintuitive finding that fixation durations near word boundaries are considerably shorter than fixation durations close to word center. Replicating Vitu *et al.* (2001), the effect was found for both single (1/1), first (1/2), and second (2/2) fixations (Sec. 5.1, p. 124).

The effects of both word frequency (Sec. 8.2, p. 215) as well as launch site distance (Sec. 7.2, p. 180) on the inverted U-shaped IOVP function mainly consisted in a vertical displacement of the curve. The same was true for an experimental manipulation where participants read the sentences of the Potsdam Sentence Corpus with reduced letter contrast (Sec. 5.2.4, p. 137). All three variables led to higher fixation durations for either low-frequency words, longer launch site distances, or words presented with lower letter contrast. Thus, the respective effect on fixation duration was independent of landing position. However, both in the reading with salient OVP condition (Exp. 3) as well as in the *z* string "reading" condition (Exp. 2) there was not only an increased vertical offset of the IOVP curve (parameter *A*) but also a stronger curvature (parameter *B'*) of the IOVP function (see below).

The Fixation-Duration IOVP effect is intriguing because the center of a word would appear to be the optimal location to fixate a word. At word center, there is a greater chance of all letters being visible, and – from the perspective of cognitive models of eye-movement control in reading – word identification should be fastest.

9.2 Modeling the Fixation-Duration IOVP Effect

9.2.1 Summary of the Suggested IOVP Model

The Fixation-Duration IOVP effect was explained as a consequence of mislocated fixations caused by saccadic errors. Thus, the introduced IOVP model expands on the consequences of oculomotor errors which produce – when large enough – mislocated fixations. McConkie *et al.*'s (1988) empirical findings on systematic oculomotor errors were replicated (Sec. 7.3.1.1, pp. 182). The main difference was that the optimal center-based launch site distance was about 5.4 letters to the left of word center whereas McConkie *et al.* reported 6 to 7 letters for English data. As a new central theoretical claim it was suggested that a new saccade program is started instantaneously if the intended target word is missed. On average, this will lead to decreased durations for mislocated fixations as opposed to well-located fixations. Importantly, by using simulations with the SWIFT model (Engbert *et al.*, 2005) it was demonstrated that the reduced duration for mislocated fixations does not imply a reduced programming time for saccades following mislocated fixations. Finally, because mislocated fixations were shown to be most prevalent at the beginning and end of words, the proposed mechanism generated the inverted U-shape for fixation durations when computed as a function of landing position.

9.2.2 Alternative Accounts of the IOVP Effect

Perceptual-economy hypothesis. The proposed IOVP model cannot account for an IOVP effect for first fixation durations in two-fixation cases, obtained in an isolated word recognition paradigm (O'Regan & Lévy-Schoen, 1987). In such a paradigm, mislocated fixations do not exist. Vitu further pursued the "perceptual economy strategy principle" (Vitu *et al.*, 2001) with a series of isolated word recognition experiments. It is suggested that at least a part of the IOVP effect is not related to mislocated fixations but to perceptual-economy processes which favor longer fixation durations at positions where greater amounts of information are anticipated (Vitu *et al.*, submitted).

In this respect, a reanalysis of Vitu's (2001) own data might be informative. In the paper, data for both fifth-grade children and adults were reported. The IOVP effect for single fixation durations turned out to be stronger for children as compared to adults (Fig. 5). With the following considerations it will be reviewed how the mislocated fixation explanation could account for that finding. Formally, according to Eq. (8) (p. 152), the strength of the generated IOVP effect depends on (1) the probabilities of mislocated fixations $p_L^{mis}(x)$ which in turn depend on landing position distributions, and (2) the difference between F_L and τ_C. First, the broader landing position distributions for children (Fig. 1 in Vitu *et al.*, 2001) are suggestive of an increased probability of mislocated fixations for children. Increased probabilities for mislocated fixations at word boundaries would be a first factor contributing to a stronger generated IOVP effect for children as compared to adults. Second, F_L in Eq. (8) reflects the mean fixation duration on words of a given length L. For children, F_L is generally higher than for adults. The saccade latency in response to a mislocated fixation, τ_C, is assumed to be similar for both children and adults. Consequently, the difference between F_L and τ_C is higher for children than for adults which would further contribute to a stronger generated IOVP effect for children as compared to adults (see also Sec. 6.2, pp. 153, for discussion on the generated IOVP effect in *z* string "reading" data). A reanalysis of the data presented in Vitu *et al.* (2001) would allow to test these considerations numerically. In contrast, it is not clear what the perceptual-economy hypothesis would predict. If longer fixation durations at the center region of a word were related to perceptual learning one could, for example, argue that fifth-grade children should show a smaller, instead of a larger, slope of the IOVP function.

Still, the "perceptual economy strategy principle" put forth by Vitu is possibly a complementary explanation to the mislocated explanation advanced here. A current collaboration with Françoise Vitu aims at experimentally determining the relative contributions of mislocated fixations and perceptual-economy strategies to the IOVP effect.

For two computational models of eye-movement control in reading it was recently reported that they were able to reproduce Fixation-Duration IOVP effects.

E-Z Reader model. A new version of the E-Z Reader model (E-Z Reader 9, Pollatsek *et al.*, 2006) is able to reproduce the IOVP effect for the first of two fixations. The effect falls out of the refixation behavior exhibited by the E-Z Reader model. First, the probability of initiating a refixation saccade is directly proportional to the distance between the initial fixation location on a word and its center. Second, the completion of L_1, the first stage of lexical access, causes the oculomotor system to program a saccade to the next word. Usually, L_1 takes shorter to complete from fixations located at word center. In this case, the refixation saccade is most likely to be cancelled. Thus, refixation saccades starting from word center only occur in cases where L_1 takes a long time to complete. This bias inflates the first of two fixations for initial fixations located near the center of a word. However, E-Z Reader 9 cannot reproduce the characteristic trade-off effect for two-fixation cases with the second fixation being shortest, rather than longest, at word center when second fixation duration is plotted conditional upon the position of the first fixation. In addition, the IOVP effect for single fixations is still a challenge for the model.

SERIF model. Furthermore, within the framework of the SERIF[67] model an alternative account for the IOVP effect has been provided recently (McDonald, Carpenter, &

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[67] **S**tochastic model of **E**ye Movements in **R**eading **I**ncorporating **F**oveal Splitting.

Shillcock, 2005). According to this model, the anatomical fact that the left and right hemi-fields of the retina project to opposite sides of the brain has consequences for subsequent saccadic guidance and linguistic processing. Within this framework, the IOVP effect is attributable to the independent computation of information content in the two hemifields coupled with a lateral inhibition mechanism between two saccadic decision units. The IOVP effect emerges because lateral inhibition is stronger at word center as compared to word edges.

Interestingly, the SERIF model would not predict the presence of a Fixation-Duration IOVP effect in meaningless letter strings since in that case the notion of information content is irrelevant. The information content of *z* strings, compared to words, is low, and it should be the same for each *z* string. However, data from a *z* string "reading" experiment clearly showed an IOVP effect which was even stronger than in normal reading control data (Sec. 5.2.1, pp. 132). Thus, the validity of the IOVP generating mechanisms in the SERIF model is seriously questioned by the existence of an IOVP effect in *z*-string "reading" data.

To summarize, in both the E-Z Reader model as well as the SERIF model, the mechanisms responsible for generating a Fixation-Duration IOVP effect are related to assumptions specific to the respective model.

9.2.3 Evidence for the Suggested IOVP Model and Limitations of the Model

In contrast, the IOVP explanation advanced here is not tied to a specific model. In principle, the mechanism that is proposed to account for the IOVP effect is compatible with any theory assuming (1) that reading saccades are directed to a specific target word, and (2) that mislocated fixations are identified and, if necessary, corrected. Cognitive models (e.g., Reichle *et al.*, 2003; Engbert *et al.*, 2005) and most oculomotor models (e.g., O'Regan, 1990; O'Regan & Lévy-Schoen, 1987; oculomotor word-targeting strategies in Reilly & O'Regan, 1998; but see Yang & McConkie, 2004; Vitu, 2003, for a different perspective) assume that an intended target word is specified for each saccade. Potentially, the occurrence of mislocated fixations might be problematic for cognitive models working on the assumption that words are processed in a serial order (see Sec. 6.5.3, pp. 174).

Ideas concerning the IOVP effect, as developed here, were implemented in the SWIFT model (see Sec. 6.3.3, pp. 162). In the SWIFT model (Engbert *et al.*, 2005), it is suggested that words are processed in parallel and that target selection is a stochastic process based on the relative strength of activations of words. In such a model, mislocated fixations are simply an additional source of stochasticity without dramatic consequences for the further processing of words. Furthermore, the mechanism of error-correcting saccades will not automatically and strictly lead to a correction of the landing positions due to the fact that target selection in SWIFT is inherently autonomous and stochastic.

Evidence from an oculomotor control condition. In this thesis it is advocated that the Fixation-Duration IOVP effect relies on low-level oculomotor mechanisms, and hence is unrelated to word identification processes. The fact that the Fixation-Duration IOVP effect also exists in the *z* string "reading" condition, and thus in the absence of word identification demands, lends strong support to this notion.

Limitations of the suggested IOVP model. The here proposed IOVP model is able to generate IOVP effects. With approximations based on empirical data, the IOVP effect was qualitatively reproduced both for normal reading data (Fig. 6.5c, p. 152) as well as mindless reading data (Fig. 6.7b, p. 155). Generally, generated IOVP curves are too flat around word center because the estimated probabilities for mislocated fixations, computed from overlapping landing position distributions, are rather low for the center region of the word. Interestingly, this shortcoming could be overcome by adding a perceptual-economy component to the model: Based on reading experience, the perceptuo-oculomotor system learns to produce longer fixations at the central region of a word because here, greater information is anticipated (cf., Vitu *et al.*, 2001).

It is thus clear that the current approximations do not always allow to reproduce quantitative differences between IOVP functions. For example, in the reading with salient OVP condition (Exp. 3), the IOVP function showed not only an increased vertical offset (as reflected in parameter *A*), but also a stronger curvature (parameter *B'*). Thus, participants did not only produce longer fixation durations as such; rather, durations were especially long when fixating at word center – in a condition where word center as the OVP was marked in red and could thus be more easily identified. Again, this could be linked to perceptual learning. However, this specific effect in the reading with salient OVP experiment should be interpreted with caution given that the experimental manipulation had an overall negative effect on eye-movement behavior: It increased single fixation durations, as well as refixation and regression probability (see Sec. 2.3.2, pp. 34).

As far as the oculomotor control condition is concerned (Exp. 2), the IOVP effect was stronger in mindless as compared to normal reading. As in the reading with salient OVP experiment, both parameters *A* and *B*' of the fitted quadratic function were significantly increased. It has been shown that the proposed IOVP model could produce the strong IOVP effect for the mindless reading condition qualitatively, but not in a quantitatively exact way (see Sec. 6.2, pp. 153). Interestingly, the perceptual-economy account would not specifically predict an IOVP effect for meaningless letter strings (Vitu *et al.*, submitted). However, IOVP effects in tasks which involve perceptual processing would not be entirely inconsistent with the perceptual-economy account.

9.3 The Refixation OVP Effect

Throughout this thesis, the refixation OVP effect was extensively investigated. As reported in earlier studies (McConkie *et al.*, 1989; Rayner *et al.*, 1996; Vitu *et al.*, 1990; Vitu *et al.*, 2001), the basic finding is that the frequency of refixating increases as the distance of the first fixation from the center of the word increases. The word refixation probability curve is well-described by a parabolic function.

In Sec. 9.3.1, variables influencing the parameters of the OVP function will be summarized and discussed. The refixation OVP effect is related to the theoretical questions of why and when refixations occur.[68] It would be desirable to identify several sub-populations of refixations reflecting different circumstances that give rise to a refixation (cf., Sec. 9.3.2). The "when" question tackles the question of pre-programming vs. directly controlled programming of refixation saccades; considerations developed on that issue are summarized and discussed in Sec. 9.3.3.

9.3.1 Influences on the Parameters of the OVP Function

First, the influence of word length on parameters of the quadratic OVP function was investigated (Sec. 3.1, pp. 62). In further analyses, the influence of additional variables including word frequency (Sec. 8.3, pp. 218) and launch site distance (Sec. 7.1, pp. 176) was examined. Furthermore, the influence of experimental manipulations on the OVP function was studied (Sec. 3.2, pp. 66). In all those analyses, data were always broken down by word length and an additional variable. Schematically, the results are compiled in Table 9.1.

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[68] Note that both questions are somewhat related.

Table 9.1 Influence of word length, word frequency, launch site distance, and experimental manipulations on the three parameters of the quadratic refixation probability curve; data were fit to $y = A + B(x - C)^2$.

FACTOR	PARAMETER		
	A	*B'*	*C'*
WORD LENGTH (EXP. 1)	++[69]	++	+
WORD FREQUENCY (EXP. 1)	++	–	–
LAUNCH SITE DISTANCE (EXP. 1)	+	–	++
Z STRING "READING" (EXP. 2)	+[70]	–	++
READING WITH SALIENT OVP (EXP. 3)	+	–	–
READING WITH A BITE BAR (EXP. 4)	+	–	–
LOW CONTRAST READING (EXP. 5)	+[71]	–	–

Mathematically, parameters *A* and *C* of the refixation probability curve reflect the vertical and/or horizontal offset of the curve, respectively, while parameter *B* is the slope of the parabolic curve (cf., Sec. 3.1, pp. 62). For a given factor, finding an effect on parameter *A*, but not on parameter *B'*, is reflective of a simple vertical displacement of the OVP curve (e.g., influence of word frequency, see below). In the same manner, finding an effect on parameter *C'*, but not on *B*, reflects a horizontal displacement of the OVP curve; this was, for example, the case when the influence of launch site distance was considered. The most complicated data pattern consists of effects on both parameters *A* and *B*, a pattern which was found for word length only.

Among all variables tested, *word length* turned out to be most influential because it affected all three parameters of the refixation probability curve. The effect on parameter *C'*, the OVP, was very small. Importantly, both parameters *A* and *B'* increased with increasing word length. Thus, the increased overall refixation probability for longer words was further modulated by initial landing position: Refixation probability was especially high after initial fixations at word edges.[72] This finding can be explained by visual acuity constraints: Longer words extend further into the periphery and thus contain letters of lower perceptibility than do shorter words. Therefore, there are more refixations of longer words when the eyes are at the same distance from the center of the word (cf., McConkie *et al.*, 1989).

Furthermore, when data were controlled for word length, *word frequency* had an independent influence which showed up in a vertical displacement of the refixation probability curve: Parameter *A* increased with decreasing word frequency. This finding

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[69] Mostly due to 8-letter words (cf., Fig. 3.2a, p. 65).
[70] But no systematic pattern (cf., Fig. 3.4a, p. 67).
[71] For longer words only (cf., Fig. 3.12a, p. 75).
[72] Note that this pattern was also found when data were controlled for word frequency.

can be explained with word identification demands at higher processing levels. More common words, i.e., words with a high frequency of occurrence in a given language, are more easily identified. In the SWIFT model, for example, maximum activation L_n of word n is related to the word's processing difficulty which in turn depends on word frequency and predictability (Engbert *et al.*, 2005). High-frequency words have a lower maximum activation than low-frequency words. With everything else being equal, lexical processing is finished earlier for high- than for low-frequency words. Thus, if the currently fixated word is of high frequency, it will either be an unlikely target for the next saccade, or it will not even be part of the set of possible targets for the next saccade. Taken together, this will lead to a reduced refixation probability for high-frequency words.

McConkie *et al.* (1989) proposed that high-frequency words require less complete visual information for identification, and this in turn reduces the need for refixations. However, this would not only predict a word frequency effect on parameter *A*, but also an additive word frequency effect on parameter *B* with a lower slope parameter for higher frequency words (see Sec. 8.3.1.2, p. 222). Contrary to that prediction and replicating previous research, the Potsdam Sentence Corpus reading data suggested that there was no effect of word frequency on the slope parameter *B*'. As reflected in the effect on parameter *A* only, curves for low-frequency words showed a higher vertical offset, at *any* initial fixation position.

In addition, *launch site distance* was identified as an additional variable influencing the parameter of the refixation probability curves. With increasing launch site distance, parameter *A* increased, and the OVP, as reflected in parameter *C'*, moved towards the beginning of the word. The additional effect of launch site distance was interpreted in terms of parafoveal preview (Sec. 7.1, pp. 176). As far as the influence of experimental manipulations on the parameters of the refixation probability curve is concerned, it is referred to the discussion in Sec. 3.3 (pp. 76).

Finally, it is interesting to note that among the variables tested, word length appears to be the only variable to influence the slope of the refixation probability curve. Neither word frequency nor launch site distance (Sec. 7.1, pp. 176) nor experimental manipulations (Sec. 3.2, pp. 66) showed a noticeable effect on parameter *B'*. While the slope of the refixation probability curve is very robust, parameters *A* and *C'* are sensitive to different variables, suggesting that refixations can be caused by different processes.

9.3.2 What Causes Refixations?

An ongoing research issue is the functional dissociation of different, more or less exclusive, sub-populations of refixation saccades (cf., McDonald & Shillcock, 2004). Several causes of refixations can be identified.

First, a proportion of refixations results from failure to identify the word due to visual acuity limitations. In that sense, sub-optimal initial landing position within a word, the length of the word, and the launch site distance are visual predictors involved in refixation planning. Initial landing position appears to be the most influential factor in that it gives rise to the parabolic shape of the refixation probability curve (cf., Sec. 3.1, pp. 62). Sub-optimal initial landing position are due to oculomotor errors. On the one hand, they make the eyes to land at a non-optimal position within word, that is they lead to an under- or overshoot of the word center as the OVP. Within the framework of the strategy-tactics theories, it was argued that refixations on a word are often caused by initially landing in a "bad" place in a word and that processing of the word is distributed across two or more fixations in such cases (O'Regan & Lévy-Schoen, 1987; O'Regan *et al.*, 1984).

On the other hand, oculomotor errors can lead to mislocated fixations, that is the eyes don't even land at their intended target word in that they undershoot or overshoot that word. Oculomotor error can thus lead to a further population of refixations that can be described as unintended. This notion was first proposed by McConkie *et al.* (1989) and was further developed in the present thesis (1) in identifying specific cases of mislocated fixations (cf., Fig. 6.2, p. 145), and (2) in estimating their prevalence. For example, in simulations with the SWIFT model (Engbert *et al.*, 2005) 3.34% of all fixations were unintended forward refixations (cf., Table 6.3, p. 158) which translated into about 27% of unintended refixations, relative to all two-fixation cases. Unintended forward refixations were found to occur mostly on longer words, with landing positions close to the end of the refixated word (Fig. 6.9a, p. 159).

Third, it was shown that there is a substantial independent influence of word frequency on the occurrence of refixations, suggesting that a proportion of refixations is due to word identification problems at higher processing levels (cf., Sec. 8.3, pp. 218). Predictability is also a factor: Refixation probability is lower for words that are highly predictable from the previous context (Balota *et al.*, 1985; Vitu, 1991c).

Fourth, the SWIFT model (Engbert *et al.*, 2005) provides an explanation for a certain subpopulation of refixation saccades. McConkie *et al.* (1989) raised the fundamental question: “Why is it that high-frequency, four-letter words are ever refixated, and more particularly, why are they sometimes refixated following an initial eye fixation at their center” (p. 252)? The authors reasoned that the *A* parameter for short, high-frequency words indicates the frequency of refixations that occur for reasons other than word recognition failure due to insufficient visual information. As a possible basis for these refixations, they suggested a previous overshooting of the target word (the initial fixation on the current word thus was mislocated, cf. Fig. 6.2, p. 145), or processing lagging behind the eye fixation pattern (cf., Kliegl *et al.*, 2006). In the SWIFT model, refixations on long words are generated because of visual acuity limitations (cf., Sec. 9.3.4, pp. 239). Refixations on short, high-frequency words mainly occur as a consequence of autonomous saccade timing and stochastic target selection. In our model, target selection is tied to the end of the labile stage of saccade programming. Lexical activations of words serve as a measure of target selection probability. High-frequency words need less time for lexical processing than do low-frequency words (see previous Sec. 9.3.1). In particular when the time point of target selection is early during the fixation, the short, high-frequency word could still show some lexical activation. Saccade target selection is realized as a competitive process among all words with non-zero lexical activation. The word with the highest activation has the best chance to be chosen as the next saccade target, yet due to stochasticity in the selection process it can happen that a short, high-frequency word is refixated. In all likelihood, such an event will be associated with a short first fixation duration, produced by the autonomous saccade timer.

Fifth, results from the z string “reading” experiment (Sec. 3.2.1, pp. 66) provided additional information about the nature of refixation saccades. The mere fact that refixations were frequently observed in this condition indicates that refixations can occur in the absence of ongoing word identification demands. The frequency of regressive refixations, however, was greatly reduced which translated into a rightward shift of the OVP as reflected in parameter *C’* of the refixation probability curve. This finding suggests that regressive refixations are predominantly related to word identification processes (but see Kliegl *et al.*, 2006). However, participants frequently exhibited progressive refixations. While the SWIFT model promotes the notion of an autonomous saccade timer, this result might suggest that, at least in z string “reading”, determination of saccade amplitude has an autonomous component: A autonomous saccade length generator leads to (progressive) refixations that are not due to visual acuity constraints and/or ongoing processing demands. Obviously, such a notion is not compatible with the notion of saccade targeting being word-based, with the center of words as an optimal landing position. Interestingly, in the *z* string "reading" data the OVP was shifted towards a position right of word center (whereas landing position distributions were almost identical to distributions computed from normal reading data). Thus, in mindless reading the eyes do not necessarily benefit from landing at OVP. In sum, the data point to the possibility that a certain proportion of refixation saccades could be somewhat randomly determined.

In this respect it is important to note that McConkie *et al.* (1989) tested whether word refixation curves in "normal" continuous reading could be explained by a random control model. They simulated sequences of fixations by randomly sampling from the empirical distribution of saccade lengths. This provided an estimated likelihood that a word of a given length would be refixated, if saccades and fixations were the result of a random process. They found that although the random control model curves were also U-shaped, they were much flatter than the curves obtained from the empirical data, and the minimum points were near word-center in the empirical data only. In a similar approach, McDonald & Shillcock (2005) established a baseline by mapping the sequences of saccades and fixations present in the so-called EMBRA eye movement corpus to random permutations of the same sentences that the participants actually read. Such a mapping simulates the situation where there is no dependence between eye movements and the material being read. The baseline data showed the major characteristics of the refixation curves: (1) the curves were roughly U-shaped, with refixation probabilities tending to increase from fixation locations on word-center outwards, and (2) the curves were asymmetrical: Refixation probability is higher when the fixation falls on the beginning than on the end of the word. However, there were also substantial differences. In particular, randomized data exhibited a much stronger word length effect on parameter *A* of the refixation probability curve. Thus, neither this baseline nor McConkie *et al.*'s random control approach provided a close fit to the empirical refixation curves. Still, these deviations do not preclude the possibility that some refixation saccades are randomly determined and thus do not depend on visual acuity constraints and/or ongoing processing demands.

The question of how refixation behavior is implemented in recent computational models of eye-movement control in reading will be discussed in Sec. 9.3.4 (pp. 239). Although the models are able to fit the empirical refixation data reasonably well, they are somewhat underspecified in that they do not account for all factors that influence the probability of refixating a word.

9.3.3 On the Pre-Programming of Refixation Saccades

Refixation saccades can be further distinguished as either being pre-planned, or as programmed during the initial fixation on the word. Due to the chosen structure of the thesis, notions on the refixation pre-programming hypothesis were somewhat distributed across the work. In the current section, they will be summarized and further discussed.

Beauvillain and colleagues argue that the refixation saccade is pre-programmed within one package together with the initial saccade into a word. As a consequence of (pre)planning a two-fixation sequence, the initial saccade is directed toward a position near the word beginning (Vergilino-Perez *et al.*, 2004; McDonald & Shillcock, 2004), and the amplitude of the actual refixation saccade is believed to be coded as a constant motor vector (Beauvillain *et al.*, 1999, 2000; Vergilino & Beauvillain, 2000, 2001; Vergilino-Perez & Beauvillain, 2004; Vergilino-Perez *et al.*, 2004). When a single fixation on a word is planned, however, the saccade is thought to be directed towards the center of the word (Vergilino-Perez *et al.*, 2004).

Taking up on work by McDonald & Shillcock (2004) and Vergilino-Perez et al. (2004) it was argued that neither differences in landing positions for refixation cases as opposed to single-fixation cases (Sec. 4.3, pp. 104) nor the lacking word frequency effect on the slope of the refixation probability curve (Sec. 8.3, pp. 218) are compelling arguments for the existence of pre-planned refixation saccades.

First, McDonald & Shillcock (2004) promoted the refixation pre-programming hypothesis (cf., Sec. 3.4.1, pp. 78) with results from corpus analyses. As Vergilino-Perez *et al.* (2004), they emphasize that landing position distributions differ for single-fixation and refixation cases. For single-fixation cases mean landing position is close to word-center, no matter how long the word is. In contrast, there was only a tiny influence of word length on the initial fixation position for the refixation cases: The mean landing position was around the second letter position.[73] The authors concluded that for at least some proportion of the refixation cases, initial saccades were not aimed at the center of the target word, but at a target location near the beginning of the word. The difference

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[73] But see Vergilino-Perez *et al.* (2004), reporting a word length effect for initial fixations followed by progressive refixations (Table 1).

in mean initial fixation position between single-fixation and refixation cases is seen as a *consequence* of refixation *pre*planning and not a *cause* of *directly controlled* refixation planning (see also Vergilino-Perez *et al.*, 2004). Current corpus analyses replicated the empirical finding, but showed that the constant mean landing position around the second letter was due to a joint consideration of both progressive and regressive refixation saccades (Sec. 4.3, pp. 104). The results considerably changed when both sub-populations were considered separately (Fig. 4.3a, p. 106), suggesting that differences in landing positions are not necessarily direct evidence in favor of the pre-programming hypothesis. Initial saccades followed by a refixation could just as well represent cases of severe within-word undershoot or overshoot, ad hoc corrected with a progressive or regressive refixation saccade.

Second, it has been argued that the lacking word frequency effect on the slope of the refixation probability curve is compatible with both the “pre-programming hypothesis” as well as the “direct control hypothesis” of refixation programming (Sec. 8.3.2, pp. 223).

It shall be emphasized that with the current work it is not argued against the existence of pre-planned refixation saccades as such. Rather, one should be more careful in interpreting empirical findings as direct evidence for pre-planning. Obtaining such evidence is indeed difficult, and was attempted with Exp. 6 where the letter-string displacement-paradigm (Beauvillain *et al.*, 1999, Exp. 1; Beauvillain *et al.*, 2000, Exp. 1) was transferred to a continuous reading situation. The results suggested that both types of refixation saccades, pre-planned and planned during the first fixation, coexist (Sec. 3.4.4, pp. 98). Acknowledging this coexistence (cf., McDonald & Shillcock, 2004; McDonald & Vergilino-Perez, 2006; Vergilino-Perez *et al.*, 2004), the question of the frequency of occurrence of pre-planned refixation sequences in reading arises. In an experiment using isolated words, 75% of refixations were estimated to be pre-planned (Vergilino-Perez *et al.*, 2004). Simulations with a computational model on eye-movement control in reading (SERIF), however, suggested that about 20% of refixation sequences are pre-planned (McDonald & Vergilino-Perez, 2006).

Notably, results presented here challenge specific assumptions inherent to the pre-programming hypothesis, as developed by Beauvillain and colleagues. In particular, the assumption that refixation amplitude is coded as a constant motor vector was tested based on data from the sentence-shift experiment as well as corpus analyses, and had to be rejected (cf., Sec. 7.3.3.4, pp. 204, where the issue of a target location for refixation saccades is discussed). In case of (pre)planning a refixation sequence on a long word, initial and refixation saccade are claimed to be programmed within one package. It appears that this "package notion" is strongly related to the assumption that refixation saccade amplitude is coded as a constant motor vector, applied after an initial fixation close to the beginning of the word. Interestingly, Vergilino-Perez *et al.* (2004; footnote 1) reported a saccadic range error for initial saccades followed by a refixation (see also McDonald & Shillcock, 2004). Furthermore, in Sec 7.3.3 (pp. 196) it was shown that the launch site – which would be the initial landing position – influences the landing position of the refixation saccade. Also, data from the sentence shifts experiment suggested that refixation saccade amplitude is not coded as a constant movement vector (Sec. 3.4.3.2, pp. 92). These data seem to undermine the "package notion". As an alternative it is suggested to understand refixation pre-planning as instances where a refixation saccade program is initiated before the execution of the initial saccade into the word, and thus acknowledging parallel programming of saccades. Furthermore, it is argued that such a pre-programming and/or parallel programming of saccades is generally possible, not only for intra-word saccades (refixations) but also for inter-word saccades. Data from the reading experiment with recurrent sentence shifts lend some support to the latter assumption. The issue is elaborated on in the next section. Guided by theoretical assumptions implemented in computational models of eye-movement control in reading, general considerations on the (pre)programming of saccades will be presented. In addition, it is discussed how refixation behavior is implemented in different models.

9.3.4 Implementation of Refixation Behavior and Saccade Programming in Computational Models on Eye-Movement Control in Reading

Proponents of the refixation pre-programming hypothesis stated, "The coexistence of two types of refixation saccades – one preplanned and the other planned during the first fixation – represents a fundamental issue for future models of eye movement control in reading" (McDonald & Vergilino-Perez, 2006).

Therefore, in the current section it will be explored how (refixation) saccade (pre-)programming is implemented in current computational models of eye-movement control in reading. First, it will be emphasized that the refixation pre-programming hypothesis is related to the more general idea that saccades can be programmed in parallel. Second, it will be argued that both the E-Z Reader model (Reichle *et al.*, 2003) as well as the SWIFT model (Engbert *et al.*, 2005) as the two currently most advanced computational models of eye-movement control in reading acknowledge that more than one saccade can be programmed at a time. Both models differ, however, in the way refixation behavior is implemented. Third, it will be shown that the architecture of the SWIFT model is in principle compatible with the notion that a certain proportion of refixation saccades is pre-planned. Fourth, it will be argued that it is reasonable to assume that the pre-programming notion generalizes to all types of reading saccades and should thus not be restricted to refixation saccades.

Parallel programming of saccades. The pre-programming hypothesis of refixation saccades relates to the more general idea that saccades can be programmed in parallel, which is not a new notion. In early models on saccadic control it was indeed assumed that only *one* saccade can be prepared and executed at a time (sequential programming). However, double step experiments demonstrated that goal-directed saccades can be programmed in parallel, i.e. the preparatory processes of two different saccades can overlap in time (Becker & Jürgens, 1979). More precisely, it was demonstrated that the presentation of a second target earlier than approximately 250 ms after the first could induce a cancellation of the saccade to the first target. A later presentation, however, led to fixations of both targets in a sequence. Acknowledging these results, both the SWIFT model (Engbert *et al.*, 2002; Engbert *et al.*, 2005) as well as the E-Z Reader model (Reichle *et al.*, 1998; Reichle *et al.*, 2003), but not the SERIF model (McDonald *et al.*, 2005) implemented the parallel saccade programming notion.

In both the E-Z Reader model as well as the SWIFT model, saccade programming is implemented as a two-stage process consisting of a labile and a non-labile stage (for illustration, see Fig. 4 in Engbert *et al.*, 2005). The following explanations consider the implementation in the SWIFT model. First, after starting a saccade program, a labile stage with an average duration τ_{lab} is entered. Second, the non-labile stage with average duration τ_{nl} is entered after the labile stage terminates. The transition from labile to non-labile stage triggers the target selection process. Finally, saccade execution is included in the model with average duration τ_{ex}. There are two basic cases of temporally overlapping saccade programs. If a new saccade program is initiated while another program is in its labile stage of development, the first program will be cancelled and only the second one will be executed. As for the SWIFT model, simulations showed that 10% of all saccades are cancelled during the labile stage (see Engbert *et al.*, 2005). The transition point between non-labile and labile stage marks that a "point-of-no-return" is passed – the saccade program cannot be cancelled anymore. Thus, if a second saccade program is initiated during the non-labile stage of the first one, both will be executed.[74] Actually, it is this latter scenario that represents parallel programming in the sense of temporally overlapping active saccade programs.

As far as this two-stage architecture is concerned, the E-Z Reader model and the SWIFT model are broadly similar; in a recent version of the E-Z Reader model further refinements were implemented (Reichle *et al.*, 2003). What triggers a second saccade program while there is currently another program active, however, is fundamentally different in the models – it is either the autonomous saccade timer (SWIFT) or ongoing processing (E-Z Reader). In the E-Z Reader model, at the end of an early stage of the word identification process (L_1), a saccade is programmed to the next word. Importantly for the current debate, the following scenario can occur (cf., Reichle *et al.*, 2003, Fig. 5, Panels D and E). During fixation on word *n*-2, a saccade program for the next word *n*-1 is initiated. While this program is in its *non*-labile stage, a program to move the eyes to word *n* is initiated. The program for word *n*-1 cannot be cancelled anymore, and thus both saccades will be executed. Consequently, the saccade program for word *n* was initiated during the fixation on word *n*-2, and thus not during the previous fixation on word *n*-1. In case of a refixation saccade, however, the saccade program is always initiated during the first fixation on the word only (see below).

Programming of refixation saccades. As a core feature of the SWIFT model, a general mechanism underlying all types of saccades is implemented; consequently, refixation saccades are treated as any other reading saccades.[75] The most recent version of the SWIFT model (Engbert *et al.*, 2005) is able to reproduce the U-shaped form of within-word refixation probabilities. Two mechanisms are responsible for the effect. First, the saccadic range error phenomenon (see Sec. 7.3.1.1.1, pp. 183) is implemented to produce a realistic variance in initial landing positions. Second, an assumed processing gradient is implemented which is strong enough to reproduce the quadratic refixation probability curves (Engbert *et al.*, 2005, Fig. 13). In SWIFT, refixations on long words are generated because of visual acuity limitations, which are incorporated by the

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[74] Typically, this will result into a rather short fixation between the two saccades.

[75] Note, however, that in the SWIFT model a modulation of saccade programming time by intended saccade amplitude is implemented (Principle 7). The modulation does not occur at the level of intersaccade intervals; rather, it affects the nonlabile stage of saccade programming. According to the saccade latency modulation principle, there is an increased saccade programming time for short intended saccade amplitudes which are mainly associated with intra-word movements (refixations).

assumption of a processing gradient. Refixations on short words mainly occur as a consequence of autonomous saccade timing (see previous Sec. 9.3.2).

The E-Z Reader model, however, makes indeed a special case about refixations in that a refixation program is initiated upon initially fixating a given word.[76] In the most recent version of the E-Z Reader model (E-Z Reader 9, Pollatsek *et al.*, 2006), the probability p of initiating a refixation saccade is a function of the absolute distance between the initial landing position on a word and the word's center as the optimal viewing position; in addition, p is scaled by the free parameter λ. Furthermore, the decision to refixate is only made after a certain time needed to take in the information about the initial fixation position.[77]

Interestingly, in the SERIF model (McDonald *et al.*, 2005) which was recently used to estimate the proportion of pre-planned refixations (McDonald & Vergilino-Perez, 2006) saccades are planned fixation by fixation. Thus, as a default parallel saccade programming does not exist. For the refixation simulations, the likelihood of a second fixation being planned with the primary saccade to the target word was stochastically determined according to a linear function of the target's length and eccentricity. Thus, in the SERIF model only very limited parallel programming is possible, namely for the case when a non-zero proportion of pre-planned refixations is specified.

Pre-programming of refixation saccades in the SWIFT model. Saccade programming in the SWIFT model is realized in a way that parallel programming and/or pre-programming is possible for any type of saccade. In the following, the pre-programming of refixation saccades within the framework of the SWIFT model is further investigated. Recall that according to the direct-control hypothesis, refixations are programmed during the first fixation on a word (see Sec. 3.4.1, pp. 78). According to the pre-programming hypothesis, however, a great proportion of refixation saccades is planned *before* the execution of the initial saccade into the word. Consequently, in terms of saccade programming both views differ in that the refixation saccade program is assumed to be initiated either *after* or *before* the beginning of the first fixation on the word. Furthermore, proponents of the pre-programming hypothesis assume that first and second saccade into the word are programmed in one package.

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[76] Note that the authors clearly misinterpret the mechanisms underlying the occurrence of refixations in the SWIFT model when claiming that in the SWIFT model, "upon initially fixating a given word, a corrective refixation saccade can be programmed and executed to move the eyes to a better viewing location".

[77] Relative to the start of the first fixation, a delay R is implemented as a free parameter.

In addition to the two-stage saccade programming notion, the SWIFT model promotes the idea of an autonomous saccade timer. As a consequence of both notions, there are quite a few instances where the program for the next saccade was initiated already *before* the start of the current fixation (cf., Sec. 6.3.4, pp. 163). Thus, it is not required that a refixation saccade program, or any other saccade program, is ad-hoc initiated during the time course of the first fixation on a word. To substantiate this claim, simulation runs based on 200 virtual subjects were performed. Analyses revealed that almost 30% of refixation saccade programs were initiated *before* the start of the first fixation on the word (Fig. 9.1).

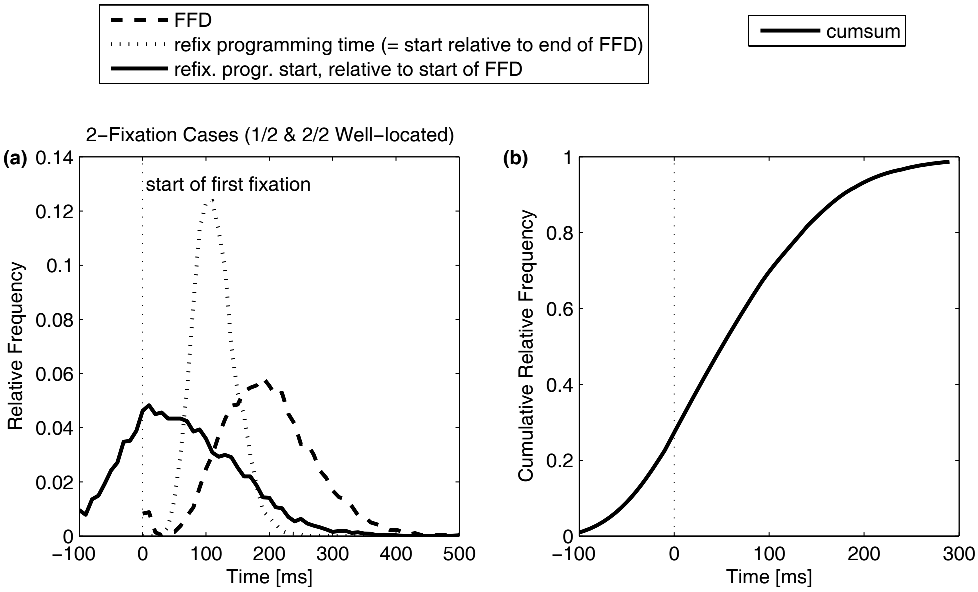

Fig. 9.1 Simulations with the SWIFT model, consideration of 2-fixation cases. (a) Fixation duration distribution for the first of two subsequent fixations on a word (broken line). Distribution of programming times (latencies) for refixation saccades following the initial fixation on a word (dotted line). Most importantly, start of the refixation saccade program relative to the start of the first fixation on a word (straight line). Here, the 0 value on the *x*-axis marks the start of the first fixation. Thus, negative values represent refixation saccade programs that were initiated before the start of the first fixation. (b) Cumulative relative frequencies for the latter distribution.

However, with the initiation of a saccade program it is not yet determined whether the program, when executed, will lead to a refixation or an inter-word saccade. Rather, this is determined by the target selection process and the computation of the saccade amplitude. The target word for the next saccade is selected at the end of the labile phase of saccade programming. The executed saccade amplitude usually deviates more or less from the intended amplitude, due to oculomotor errors. Consequently, the virtual eyes sometimes land on a different than the intended target word. For example, refixations can fail, just as unintended refixations can occur (see Fig. 6.2, p. 145). Because target selection is tied to the end of the labile phase of saccade programming it occurs rather towards the end of a given fixation. Therefore, it is usually decided only during the time course of the initial fixation on a word whether the next saccade is going to be a refixation saccade. In principle, one could think about changing the time point of target selection. Still, unlike suggested by Beauvillain and Vergilino, in the SWIFT model first and second saccade are not programmed in one package. There is, however, no apparent reason why the oculomotor system should treat refixation saccades so much differently than any other saccade. Thus, as in the previous section it is argued against the "package notion". As far as landing positions are concerned, in SWIFT a saccadic range error with parameters estimated from the Potsdam Sentences Corpus data (cf., Sec. 7.3, pp. 182) is applied to both inter-word as well as intra-word saccades (Engbert *et al.*, 2005). Based on results from continuous reading data it was implemented that the landing position for the refixation saccade, and thus refixation saccade amplitude depends on initial landing position[78], which is at odds with the "constant motor vector assumption" put forth by Beauvillain and colleagues. Interestingly, it appears that the notion of refixation saccade amplitude being coded as a constant movement vector has not been implemented in the SERIF model either (McDonald & Vergilino-Perez, 2006).

From the perspective of the pre-programming hypothesis it is proposed that there is a pre-established organized plan for the refixation saccade "that could constitute a unit of motor action encoded with the primary saccade and memorized before the execution of the last one" (Vergilino-Perez & Beauvillain, 2004). Unfortunately, in none of the papers it is explicated in detail how and when the two amplitudes and saccade latencies are to be computed. A possible scenario is pictured in Fig. 9.2. It displays a 2-saccade sequence leading to an immediate refixation of the word "refixation". *SL* denotes saccade latency which is defined as the time needed to plan and execute a saccade. The time axis starts with a first saccade program (cf., *SL* 1) which is terminated by the execution of the initial saccade into the word (*S1*); the saccade moves the eyes 7 letters in length and makes them land at the third letter of the 10-letter word "refixation". *S1* is followed by the first fixation on the word (*F1*). Three variants of possible saccade latencies related to the second saccade (*S2*) which is the refixation

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[78] Recall that initial landing position is the launch site for the refixation saccade.

saccade are depicted (*SL* 2a, *SL* 2b, *SL* 2c). The second saccade is followed by the second fixation, i.e. the refixation, on the word (*F2*).

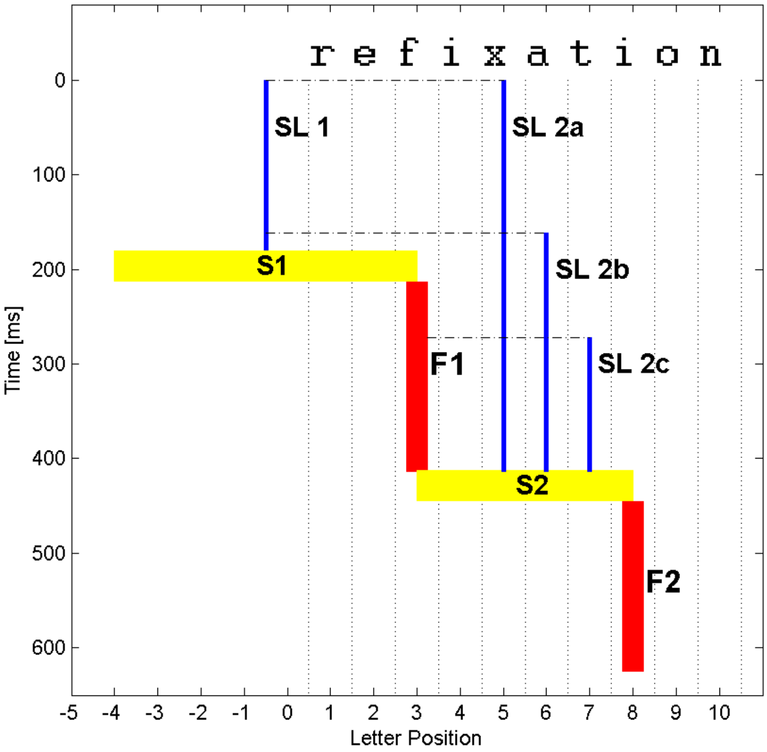

Fig. 9.2 Time-space diagram for a 2-saccade sequence leading to an immediate refixation of the initially fixated word. *S1* initial saccade into the word, *S2* refixation saccade. *F1* first fixation on the word "refixation", *F2* second fixation on the word. *SL* saccade latency (for details, see text).

Relevant for the current debate is the latency of the refixation saccade (*SL* 2). *SL* 2a visualizes the scenario apparently assumed by Beauvillain and Vergilino: Both saccade programs, *SL* 1 and *SL* 2, are initiated at the same time. As becomes evident from the figure, this would lead to an extremely prolonged saccade latency for the refixation saccade (*SL* 2a). *SL* 2b, on the other hand, covers the case that *SL* 1 and *SL* 2 partly overlap in time. Finally, *SL* 2c reflects the traditional view that the refixation saccade is programmed ad hoc during the initial fixation on the word (e.g., O'Regan, 1990). Note that cases b) and c) can occur in the SWIFT model.

In the SWIFT model, all saccade latencies are randomly sampled from a gamma distribution while lexical activation can delay the initiation of a saccade program via the inhibition by foveal lexical activity. Still, the majority of *short* FFD will be related to the situation pictured by *SL* 2b, whereas *longer* FFD are likely to be related to *SL* 2c (cf., Sec. 6.3.4, pp. 163, for considerations on the latency of mislocated fixations). This goes along nicely with the results by Beauvillain and Vergilino (2000), where short first fixations are related to pre-programmed refixation saccades whereas long first fixations indicate a revision of pre-planned refixation saccade programs and/or ad-hoc programming during the first fixation on a letter string. Results from the reading with recurrent sentence shifts experiment were discussed in a similar manner (cf., Sec. 3.4.4, p. 98). Likewise, Radach *et al.* (1999) related short fixation durations to parallel saccade programming.

To promote the refixation pre-programming hypothesis, it is argued that in case of long words, it is less costly for the saccadic system to plan a two-saccade sequence than to program a second fixation during the first fixation (McDonald & Vergilino-Perez, 2006). In the same manner, McDonald & Shillcock (2004) argue that "canceling a saccade may be less costly in processing terms than programming an additional fixation on the target item" (p. 1042). While these considerations might be reasonable it should be noted that saccade programming as implemented in the SWIFT model imposes no extra costs for refixations. Furthermore, it is economic – both in terms of programming costs for the oculomotor system as well as in terms of minimal modeling – to assume one general programming mechanism underlying all types of saccades (cf., Engbert *et al.*, 2005).

Finally, Beauvillain and Vergilino provided empirical evidence for refixation saccade programs being subject to *cancellation* (2004). In both the SWIFT model as well as the E-Z Reader model, *any* type of saccade can be cancelled. It is true, however, that neither model allows to *adjust* the amplitude of a saccade in response to, for example, a word length change (cf., Vergilino & Beauvillain, 2000), but note that these experimental paradigms (letter string length change, letter string displacements) were employed to make a pre-programming of saccades visible. In a normal reading situation we are neither faced with length changes nor sentence displacements.

To summarize, according to Beauvillain and Vergilino a great proportion of refixation saccades is pre-programmed with the initial saccade into the word. In general, in this thesis it has been suggested to relax that assumption in abandoning the "package notion". In the present section, it has been argued that the pre-programming hypothesis is related to the more general idea that saccades can be programmed in parallel. Parallel programming, in turn, is related to the incident that a given saccade program was initiated *before* the execution of the previous one. To a varying degree, this notion has been implemented in computational models. In the SERIF model, parallel saccade programming is limited to a given proportion of refixations (McDonald & Vergilino-Perez, 2006). In the E-Z Reader model (Pollatsek *et al.*, 2006), to a certain degree inter-word saccades can be pre-programmed while refixation saccades are initiated after the beginning of the first fixation on a word. In the SWIFT model (Engbert *et al.*, 2005), however, both inter-word saccades as well as refixations can be pre-programmed, a set-up which is in line with results from the sentence-shifts experiment (Exp. 6).

9.4 The Preferred Viewing Location

For both single fixations as well as fixations following regressive inter-word saccades, landing positions were clustered around word center. In two-fixation cases, landing position distributions were shifted toward the ends of words (Fig. 5.3, p. 127, for forward refixations; Fig. 5.4, p. 128, for backward refixations). Given that only about 10-15% of reading saccades are refixations, the contribution of landing positions related to refixation cases to the overall PVL curve is rather small. In addition, the landing position effects of first and second fixations in forward and backward refixation cases might cancel each other out. Therefore, when considering *all* fixations (Fig. 6.1, p. 142), results turned out to be similar to results for *single* fixations (Fig. 4.1, p. 101).

Interestingly, the influence of experimental manipulations on the PVL, based on all fixations, was negligible. (Sec. 4.4, pp. 107). If leaving the reading with sentence shifts experiment aside, only the bite bar condition led to modulations of landing position distributions. It is thus concluded that the "preferred viewing location" is a remarkably robust phenomenon.

Word frequency had a very small effect only (Sec. 8.1, pp. 211). Furthermore, landing position distributions were remarkably similar in *z* string "reading" as opposed to normal reading (Sec. 4.4.1, p. 107). Both findings suggest that where the eyes land within a word is not so much influenced by ongoing linguistic processing. Rather, replicating findings by McConkie *et al.* (1988) it was shown that landing positions on words following progressive inter-word saccades are primarily determined by the launch site distance (Sec. 7.3.1.1, pp. 182).

9.5 On the Relation between OVP and PVL

So far, there has been rather limited understanding of the relation between PVL and OVP. Currently, three more or less exclusive accounts can be found in the literature.

A first explanation for why readers tend to fixate the PVL, as opposed to the OVP, is related to parafoveal processing during fixations in reading (for details, see Rayner *et al.*, 1996). The so-called *parafoveal preview benefit* refers to the finding that skilled readers pick up information from the parafoveal word $n+1$ while they are still fixating on word n. This can be concluded from the fact that the reading pace slows down when letter information from the parafoveal word is denied (e.g., because the word remains masked until the eyes land on it). With other words, parafoveal preprocessing of a word facilitates its subsequent foveal processing. As for landing positions, it is assumed that readers often move their eyes to a position in a following word at or beyond the margin from which information was obtained parafoveally in the previous fixation (Rayner *et al.*, 1996). As a consequence, preview benefit should predict landing position distributions, a hypothesis that would need to be tested experimentally.

However, a prediction that can be tested with the current data can be derived from the parafoveal preview hypothesis. Little or no letter-level information is acquired during reading more than about 7 or 8 letter positions to the right of the currently fixated letter (Underwood & McConkie, 1985). Therefore, the parafoveal preview hypothesis would predict a nonlinear relationship between launch site distance and mean landing site (McConkie *et al.*, 1988). More specifically, a negatively-accelerated curve that asymptotes at a launch site no more than 7 letter positions to the left of the word would be predicted. However, for different sets of reading data (English and German), for progressive inter-word saccades a *linear* relationship between launch site distance and mean landing site was found (McConkie *et al.*, 1988; McConkie *et al.*, 1994; Radach & McConkie, 1998). For German reading data based on the Potsdam Sentence Corpus (Exp. 1, $N = 245$), this key finding was replicated (Sec. 7.3.1.1.1, pp. 183). It is true, however, when the corresponding analyses for the present data are extended to very long launch site distances, the landing position function asymptotes (see also Radach & McConkie, 1998), but the function as such is clearly not negatively-accelerated. To summarize, the SRE phenomenon is not compatible with the parafoveal preview hypothesis.

According to the second account, there is a strong relationship between OVP and PVL. Numerous studies showed that word recognition performance is best from locations that are fixated most frequently during reading (O'Regan & Jacobs, 1992). According to the "perceptual learning" account, frequently fixated positions are becoming optimal for word recognition (e.g., Nazir, 2000). In that sense, PVL is predictive of the OVP. It is unclear, however, how these results from isolated word recognition studies generalize to normal reading. It needs to be examined whether there is a correlational or even causal relationship between OVP and PVL in continous reading.

A third explanation, which is certainly the one promoted with the concept of this thesis, relates both OVP and PVL to low-level visuomotor factors (McConkie *et al.*, 1989; McConkie *et al.*, 1988). When proficient readers move their eyes to a new word, they send them to a functional target location at or near the center of that word, the location at which refixation probability is at its minimum (the OVP). However, there are two sources of error that cause the eyes to deviate from that optimal location: (1) a systematic saccadic range error, by which the system tends to overshoot near targets and undershoot far targets (Kapoula, 1985; Kapoula & Robinson, 1986), and (2) a random error that produces the Gaussian distributions observed. Refixation probability curves suggest that these oculomotor errors have a substantial negative effect on reading time. The effect of both sources of error is to reduce the frequency with which the eyes land at the OVP. This, in turn, increases refixation probability, and thus total reading time. Consequently, according to this account the reason why readers typically fixate the PVL instead of the OVP is because of oculomotor errors in saccade programming and execution (see also O'Regan and Lévy-Schoen, 1987).

9.6 Résumé of Experimental Manipulations

Due to the chosen structure of the thesis, results of experimental manipulations were presented and discussed somewhat distributed across the work. The current section provides a global evaluation.

Z string "reading" as an oculomotor control condition (Exp. 2). One of the currently most relevant research issues is to determine the relative influences of low-level perceptual factors and higher-level cognitive factors on eye movements during reading (Starr & Rayner, 2001). This issue was approached in Exp. 2 where a z-string version of the Potsdam Sentence Corpus was created as an oculomotor control condition to the original reading experiment. In the experiment, higher-level lexical, semantic, or syntactic processes involved in reading were virtually removed. Not surprisingly, across all experiments this manipulation had the strongest impact on eye-movement behavior. Global analyses showed that fixation durations were prolonged and the length of progressive saccades was shortened in *z* string "reading" as compared to normal reading. It appears that in normal reading the eyes are pulled forward by semantic (para)foveal information. Furthermore, regressive inter- as well as intra-word saccades were considerably reduced in *z* string "reading". The data were informative with regard to the nature of refixations in reading. Interestingly, overall landing position distributions were very similar in both conditions, suggesting that where the eyes land within a word is not influenced by ongoing linguistic processing.

Finally, it was shown that the Fixation-Duration IOVP effect does exist in the *z* string "reading" condition, hence in the absence of word identification demands. On the one hand, this lends strong support to the explanation developed in this thesis, advocating that the Fixation-Duration IOVP effect relies on low-level oculomotor mechanisms. On the other hand, it seriously questions the explanation for the IOVP effect as proposed within the framework of the SERIF model (McDonald *et al.*, 2005).

In sum, dependent on which theoretical camp one belongs to (cf., Sec. 1.3, p. 13), the existing differences between mindless and normal reading can be interpreted either in terms of an "astonishing resemblance" (Vitu *et al.*, 1995, p. 361) or as fundamental differences (Rayner & Fisher, 1996). For future research, it would be interesting to scale down the SWIFT model to a primary oculomotor model and see how adequately it can account for eye-movement control in reading. In the same manner it would be interesting to model the *z* string "reading" data as such. In perspective, it would be beneficial to develop an experimental paradigm that captures mindless reading, in the sense of reading while thoughts stray off the text, more closely than the *z* string scanning paradigm.

Reading with salient OVP (Exp. 3). The experiment aimed for creating a reading situation that would elicit automatic oculomotor capture. For certain words of the Potsdam Sentence Corpus, the optimal landing letter was marked in red and thus acted as a salient exogenous stimulus. It was hypothesized that the red letter might attract the eyes in terms of automatic oculomotor capture. To sum up quickly, it was an unsuccessful manipulation. The standard deviation of landing position distributions could not be reduced with this kind of manipulation. On the contrary, it had a rather negative effect on reading behavior: Single fixation duration, regression probability, as well as refixation probability and consequently total reading time were significantly increased. Different than in most of the studies using the oculomotor capture paradigm (cf., Godijn & Theeuwes, 2003), in the current reading experiment the red letter did not have an *abrupt* onset. One could therefore think of a follow-up experiment where the red letter appears with a sudden onset. For example, as soon as the to be marked word appears in parafoveal vision, the color of the OVP letter could be switched from black to red. However, the results from the current as well as other studies point to rather modest prospects of success for such a manipulation.

Reading with low letter contrast (Exp. 5). What is interesting about the low contrast manipulation is that it prolonged single fixation duration, while saccade lengths and other spatial aspects of eye-movement behavior like skipping and refixation probability remained unaffected. Importantly, the reduced visibility of the text did not affect refixation behavior. It is generally assumed that the parabolic shape of the refixation OVP curve is due to the rapid drop of visual acuity with distance from the center of the fovea (McConkie *et al.*, 1989). This acuity drop-off within the fovea diminishes the visibility of letters that are not directly fixated. Refixations are thus more likely to occur when the eyes initially land at either end of the word. It was predicted that an experimentally induced reduction of the letter contrast should affect both the vertical offset and the slope of the refixation OVP curve (see Sec. 3.2.4, p. 74). However, the slope of the refixation OVP curve was not affected by the low contrast manipulation; if anything, there was a slightly increased vertical offset of the curve for longer words. This finding casts a bit of a shadow on the generally accepted assumption that the drop-off of peripheral acuity forms the primary basis for the parabolic shape of the refixation OVP effect (see also Nazir, 1991). Rather, it points to the possibility that a proportion of refixations are simply caused by properties of the oculomotor system (cf., Sec. 9.3.2, pp. 234). In sum, readers adjusted to the low contrast condition in that they prolonged the time to stay on a word which could be read with one fixation. The decision of where to move the eyes, however, was not adjusted which is evidence in favor of “when” and “where” decisions being quite independent (cf., Sec. 1.2, p. 11).

Reading with a bite bar (Exp. 4). In a next experiment, participants read the sentences of the Potsdam Sentence Corpus with their heads fixed with a bite bar. This condition was compared to the default experimental setup in the Potsdam laboratories where participants’ head is stabilized with a chin rest. In natural reading, eye movements are frequently accompanied by head movements in reading direction. Working with a chin rest reduces head movements, but they are completely precluded when a bite bar is used. The eye-movement data in both conditions were remarkably similar, except for one specific difference. When participants had the head fixed with a bite bar, landing position distributions were shifted to the right and had a greater standard deviation. It appears that in the bite bar condition readers overcompensated for the suppressed head movements in that they tended to send their eyes further into the target word than in the less constrained chin rest condition. This significant shift in landing position distributions was accompanied by an increased skipping probability that just failed to be significant (p = .08). In perspective it would be interesting to compare these data with a completely unconstrained reading condition. This would require an eye tracking setup that allows to measure both eye movements as well as head movements with a sufficient accuracy.

Reading with recurrent sentence shifts (Exp. 6). Experiment 6 was certainly the most complicated experiment, both in terms of implementation as well as data analysis and interpretation of results. By displacing the sentence during saccades, changes in landing position were experimentally induced. Since these sentence displacements occurred frequently, this manipulation was quite a brutal intervention. Global analyses comparing data from the sentence shift experiment with normal reading control data revealed that eye movements were surprisingly unperturbed by the sentence displacements. There were, however, specific oculomotor responses to the sentence shifts that were analyzed and interpreted from the perspective of a possible pre-programming of (refixation) saccades. It was concluded that both types of refixation saccade programs – pre-planned vs. triggered during the initial fixation – coexist. Furthermore, it was argued that the notion of pre-planned saccades should be extended from intra-word to inter-word saccades. In general, it is rather difficult to obtain conclusive empirical evidence in favor of saccade pre-programming. The sentence-shift manipulation created a highly dynamic reading situation which turned out to be difficult to unravel with analyses of empirical data. In perspective, modeling the sentence shift data appears to be an interesting issue for future research. Computational modeling allows to make the processes believed to be involved in saccade programming transparent. Likewise, it would be an interesting though challenging issue for future research to continue the transfer of ideas behind different double-step paradigms developed by Beauvillain and colleagues to a normal reading situation. It might also be worthwhile to employ the sentence-displacement paradigm in a more controlled version than the one chosen for the current experiment. In that way, results from the current experiment could be further explored.

10 Conclusion

The starting point for this thesis was formed by an extremely rich data base of German eye-movement data collected from 245 participants having read the 144 sentences of the Potsdam Sentence Corpus (Exp. 1). It provided an opportunity to evaluate a number of findings related the *optimal* and *preferred viewing position* in reading as investigated in previous studies. The results confirmed and specified a number of classic results reported in earlier studies. When studying the influence of launch site distance on OVP and PVL, the present work considerably extended prior results, especially because refined methods of analysis were developed. In addition, the influence of experimental manipulations on parameters of the refixation OVP curve and/or PVL curves was systematically investigated.

While OVP and PVL are established empirical findings, conclusive evidence for the Fixation-Duration Inverted-Optimal Viewing Position effect was only recently provided (Vitu *et al.*, 2001). From the perspective of cognitive models of eye-movement control in reading (e.g., Reichle *et al.*, 2003), word identification should be fastest, not slowest, when fixating at word center, i.e. the OVP. According to the strategy-tactics theory (O'Regan, 1990, 1992) as the most prominent example of an oculomotor model, single fixation duration should be independent of landing position. Thus, both oculomotor and cognitive models of eye-movement control in reading fail to predict the Fixation-Duration IOVP effect. The novel contribution of the thesis was to identify mislocated fixations as a major factor contributing to the effect. Their prevalence was estimated from extrapolations of landing position distributions beyond word boundaries. Given the fact that they occur quite frequently, the role of mislocated fixations for theory building and data analysis was emphasized. The proposed mechanism for generating the IOVP effect is generally compatible with both oculomotor and cognitive models of eye-movement control in reading. It is concluded that the Fixation-Duration IOVP effect might evolve into an important boundary condition for computational models of eye-movement control during reading.

This thesis clearly embraced landing-position related phenomena. Comprehensive analyses of landing position distributions showed that *where* the eyes land within a word is mainly determined by “low level” visuomotor variables, that is word length and, most importantly, launch site distance. As a variable, initial landing position gives rise to the parabolic refixation OVP effect as well as to the Inverted-Optimal Viewing Position effect for fixation durations. An important issue for future research is to investigate why the slope of the OVP and/or IOVP function is fairly robust against both higher-level and lower-level influences. The slopes were neither much affected by word frequency nor by launch site distance.

Refixations are certainly another topic of future research, in particular with respect to modeling. Current computational models of eye-movement control in reading are somewhat underspecified in that they do not account for all factors that influence refixation behavior.

A further issue for future research is to explore the relation between PVL and IOVP curves; landing position distributions and Fixation-Duration IOVP curves tend to be somewhat similar in shape. Finally, it would be interesting to further study the interrelations between all three landing-position related phenomena – OVP, PVL, and IOVP.

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12 Appendices

Appendix A

Experiment 1 (Original Reading Experiment): Detailed Information on Participants

Subject Number	Subject Code	Age	Sex	Vocabulary	Digit Symbol	Eye Dominance	Missing Sentences
1	ap1	66	male	33	39		7
2	ap2	70	female	32	58		20
3	ap3	74	female	35	44		32
4	ap4	73	male	33	47		0
5	ap5	74	female	34	61		0
6	ap6	72	male	32	63		8
7	ap7	74	female	32	50		4
8	ap8	73	male	34	66		28
9	ap9	71	male	36	60		4
10	ap10	66	female	31	50		22
11	ap11	64	male	33	55		7
12	ap12	71	male	35	43		25
13	ap13	76	male	33	43		4
14	ap14	71	male	33	38		15
15	ap15	70	female	34	52		2
16	ap16	67	female	34	45		3
17	ap17	68	female	33	65		38
18	ap18	66	female	34	50		10
19	ap20	75	male	33	36		30
20	ap51	68	female	34	48		7
21	ap53	74	male	31	42		2
22	ap54	69	male	32	44		6
23	ap56	72	female	34	44		17
24	ap58	72	male	33	41		38
25	ap60	72	male	33	69		0
26	ap61	66	female	32	36		9
27	ap64	71	male	34	53		20
28	ap65	66	male	33	38		8
29	ap66	84	male	33	48		28
30	ap67	71	female	33	69		1
31	ap69	67	female	33	45		6
32	ap75	57	male	30	36		11
33*	jp1	19		35	78		0
34*	jp2	18		33	65		7
35*	jp3	27		34	71		7
36*	jp4	20		33	62		3
37*	jp5	23		32	77		0
38*	jp7	18		32	72		0
39*	jp8	19		33	67		15
40*	jp11	20		33	55		1
41*	jp12	23		32	64		10
42*	jp13	21		32	85		11
43*	jp14	19		33	60		5
44*	jp15	20		34	83		1
45*	jp16	26		33	53		5
46*	jp17	21		32	63		6
47*	jp18	19		34	64		4
48*	jp19	23		34	66		5
49*	jp20	20		32	68		3
50*	jp21	21		32	59		7
51*	jp22	19		34	68		1
52*	jp23	25		33	76		4
53*	jp24	20		33	77		5

54*	jp25	21		32	64		1
55*	jp26	20		33	71		1
56*	jp27	21		32	76		4
57*	jp28	21		32	78		4
58*	jp29	23		31	65		1
59*	jp30	21		32	61		42
60*	jp31	19		33	58		14
61*	jp32	20		33	67		0
62*	jp33	23		34	78		1
63*	jp34	19		33	67		3
64*	jp35	22		34	64		2
65*	jp36	20		31	58		18
66	ap21	71		30	60		6
67	ap22	66		32	50		4
68	ap23	75		33	68		9
69	ap24	71		29	45		8
70	ap26	72		32	53		12
71	ap27	72		32	47		6
72	ap29	67		32	44		13
73	ap30	79		34	35		49***
74	ap31	73		32	49		43
75	ap33	71		33	45		41
76	ap34	72		32	49		64***
77	ap35	72		33	43		22
78	ap36	71		32	40		6
79	ap38	72		31	42		13
80	ap39	76		32	45		26
81	ap40	71		34	53		3
82	ap41	66		34	45		4
83	ap42	66		33	50		56*
84	ap43	71		30	46		7
85	ap44	74		36	43		7
116*	jp40	23		67	34		18
117*,**	jp41	21		63	31		9
118*,**	jp42	20		69	27		3
119*	jp43	28		75	35		3
120*	jp44	22	female	n.a.	n.a.		16
121*	jp45	22		68	33		9
122*	jp47	31	male	56	36		5
123*	jp49	25	male	n.a.	n.a.		8
124*	jp50	23		61	29		10
125*	jp51	20		76	33		1
126	jp52 (z)	20		83	33		66***
127*	jp53	20		55	32		4
128*	jp54 (z)	24	male	n.a.	n.a.		0
129*	jp57	20		56	31		30
130*	jp58	21		71	28		8
131*	jp59	20		67	32		17
132*	jp60	20		59	32		5
133*	jp61	20		74	32		3
134*	jp62 (z)	25		65	33		33
135*	jp63b	n.a.		n.a.	n.a.		2
136	jp65	n.a.		n.a.	n.a.		57***
137*	jp66	20		56	28		2
138*	jp67	n.a.		n.a.	n.a.	n.a.	14
139*	jp69	n.a.		n.a.	n.a.	n.a.	4
140*	jp72	n.a.		n.a.	n.a.	n.a.	4
141*	jp73	23		54	33		5
142*	jp74 (z)	20		61	31		17
143*	jp75	23		84	33		1
144**	AP79	18	female	30	54		10

145	AP107	43	female	35	66	9
146	AP108	48	female	33	64	2
147	AP109	35	female	32		13
148	AP110	45	female	31	61	12
149*	AP111	22	male	35	66	3
150	AP112	42	female	32	48	87***
151	AP113	n.a.	n.a.			2
152	AP114	63	male	31	44	45***
153	AP115	30	female	33	65	7
154	AP116	49	female	34	39	8
155	AP117	44	female	34	62	33
156	AP118	66	male	34	38	3
157	AP119	48	female	31	45	1
158	AP120	56	female	31	44	20
159	AP121	66	female	31	48	4
160	AP122	64	female	35	55	13
161	AP123	35	female	35	65	11
162	AP124	46	female	33	45	1
163**	AP125	17	male	30	56	11
164**	AP126	17	female	32	86	7
165**	AP127	18	female	34	58	0
166	AP128	53	female	31	61	23
167**	AP129	19	male	28	50	8
168**	AP130	17	female	33	64	28
169**	AP131	18	female	33	59	7
170**	AP132	19	female	30	64	1
171**	AP133	16	male	26	48	25
172**	AP134	17	male	33	42	24
173**	AP135	18	female	33	60	6
174**	AP136	18	female	32	52	12
175**	AP137	17	female	29	61	38
176	AP138	17	male	32	71	57***
177	AP139	21	male	30	71	10
178*	AP140	23	female	27	69	0
179**	AP152	17	male	29	54	3
180	AP153	65	female	34	59	66***
181	AP154	49	female	34	68	6
182	AP155	50	female	34	51	24
183	AP156	62	male	28	51	4
184	AP157	62	female	36	53	3
185	AP158	72	male	34	64	2
186	AP159	79	male	34	51	30
187	AP160	39	female	30	56	4
188	AP161	41	male	30	45	7
189	AP162	48	female	32	61	14
190	AP163	64	female	36	44	49***
191	AP165	64	male	33	34	0
192	AP166	66	male	32	42	2
193	AP167	76	male	34	59	81*
194	AP168	72	female	30	41	102***
195	AP169	61	female	34	50	43
196	AP170	64	female	34	55	35
197	AP171	63	female	32	52	7
198	AP172	41	female	35	47	13
199	AP173	63	female	33	49	8
200	AP174	47	female	31	49	47***
201**	AP175	19	female	32	54	1
202*	AP176	27	female	34	72	27
203**	AP177	19	female	32	66	10
204	AP178	17	female	30	63	94***
205**	AP179	19	female	31	83	11
206**	AP180	16	female	29	66	5

207**	AP181	19	female	33	68		7
208**	AP182	19	female	31	71		33
209	AP183	18	female	31	56		2
210**	AP184	17	female	32	47		7
211**	AP185	17	female	26	66		15
212**	AP186	17	female	28	69		21
213	AP187	18	female	26	72		46***
214*	AP188	38	male	n.a.	56		3
215**	AP189	17	female	33	61		30
216	AP190	18	female	33	72		9
217**	AP192	17	male	32	59		1
218	AP194	38	female	34	58		25
219	AP195	60	female	32	40		46***
220	AP197	20	male	29	61		5
221	AP198	18	male	30	61		1
222	AP199	18	male	33	73		3
223	AP200	18	male	27	51		2
224**	JP101	19	female	31	54		5
225	JP102	18	female	26	66		33
226**	JP103	17	female	26	65		1
227**	JP104B	17	female	31	45		23
228	JP105	18	female	26	73		59***
229	JP106	18	female	21	70		17
230	JP107	19	female	31	77		137***
231*	jp76	22	female	32	62	right	0
232*	jp77	22	male	31	57	left	14
233*	jp78 (z)	22	male	33	52	right	5
234*	jp79	20	female	31	57	left	4
235*	jp80	22	female	32	48	right	6
236*	jp81	37	female	34	62	right	2
237*	jp82	n.a.	n.a.	n.a.	n.a.	n.a.	1
238*	jp83 (z)	23	female	30	60	left	23
239*	jp84	23	n.a.	n.a.	n.a.	n.a.	3
240	jp85 (z)	20	female	31	64	left	51***
241*	jp86 (z)	20	female	32	69	right	10
242*	jp87	21	female	32	52	left	21
243*	jp88	25	n.a.	n.a.	n.a.	n.a.	7
244*	jp89	24	male	34	55	right	1
245*	jp91	21	female	n.a.	n.a.	n.a.	14
246*	jp92 (z)	19	female	31	64	right	18
247*	jp94 (z)	22	male	33	46	right	3
248*	jp95 (z)	19	female	33	82	right	17
249*	jp96	27	male	32	56	right	0
250*	jp97 (z)	20	female	31	65	right	10
251*	jp98 (z)	22	n.a.	n.a.	n.a.	right	0
252*	jp99 (z)	21	female	31	48	left	0
253*	jp100 (z)	22	male	31	62	right	15
254*	jp103 (z)	23	female	34	75	left	0
255*	jp104 (z)	22	n.a.	n.a.	n.a.	left	3
256*	jp105	22	female	34	55	right	0
257*	jp106 (z)	20	female	34	58	right	3
258*,**	jp107 (z)	26	male	34	64	light	8
259*	jp108 (z)	23	male	34	48	right	4
260*	jp109 (z)	24	female	31	69	left	3
261*	jp111 (z)	21	female	31	57	left	15
262*	jp112 (z)	21	female	30	52	right	0
263*	jp113 (z)	21	female	33	56	left	4
264*	jp116 (z)	20	female	36	54	right	4
265*	jp117	20	female	33	67	right	8
266*	jp118	24	female	n.a.	n.a.	right	1
267*	jp119	20	female	n.a.	n.a.	right	3
268*	jp120	22	male	34	60	right	0

269*	jp121	37	female	33	46	left	31
270*	jp122	25	female	35	68	right	15
271*	jp123	20	female	31	73	right	18
272*	jp124	19	female	33	57	left	12
273*	jp125	28	male	35	58	right	1
274*	jp114	23	male	30	49	right	8
275*	jp115	24	female	32	50	right	14

Note. In this documentation for the original PSC reading experiment, running subject numbers 86-115 represent the subjects participating in the reading with low contrast experiment, see Appendix G. Subjects 1-85 were tested with a SR Research EyeLink I system (250 Hz) while subjects 116-275 were tested with a SR Research EyeLink II system (500 Hz).

*Participants served as a control group for Experiments 3, 5, and 6.

**Participants served as a control group for Experiment 4.

***Participant thus contributed less than 100 (out of 144) valid sentences. For participant-based statistics, these data were excluded from analyses.

Appendix B

Experiment 2 (Z String “Reading”): Detailed Information on Participants

Subject Number	Age	Sex	Vocabulary	Digit Symbol	Eye Dominance	Missing Sentences
1 = era29	22	female	31	54	right	10
2 = sal18**	22	female	28	70	left	3
3 = era27	22	female	34	56	right	1
4 = era21	21	male	33	56	right	3
5 = era03	21	female	34	67	right	2
6 = era12	27	female	28	59	right	1
7 = era38	20	female	34	64	right	2
8 = era37	21	male	31	60	left	6
9 = era02	22	female	24	69	left	8
10 = era39	20	female	31	36	right	2
11 = jp78**	24	male	33	52	right	1
12 = era42	24	male	n.a.	n.a.	left	0
13 = sal31**	30	female	32	59	left	7
14 = jp86**	21	female	32	69	right	0
15 = jp74**	22	female	31	61	left	8
16 = jp85**	22	female	31	64	left	10
17 = jp83**	25	female	30	60	left	3
18 = era44	21	female	26	55	left	4
19 = jp52**	22	male	33	61	left	10
20 = sal32**	20	female	34	51	right	3
21 = era45	22	female	32	67	right	1
22 = sal21**	22	female	33	55	left	0
23 = jp62**	27	female	32	62	right	2
24 = jp92**	19	female	31	64	right	6
25 = jp94**	22	male	33	46	right	0
26 = jp100**	22	male	31	62	right	1
27 = jp95**	19	female	33	82	right	10
28 = jp98**	22	male	30	58	right	6
29 = jp99**	21	female	31	48	left	0
30 = jp97**	20	female	31	65	right	3
31 = era11	20	female	28	64	right	21
32 = jp96**	27	male	32	56	right	4
33 = sal26**	25	female	31	68	right	0
34	28	male	35	62	right	2
35 = jp103**	23	female	34	75	left	0
36 = jp104**	22	n.a.	n.a.	n.a.	right	6
37 = jp106**	20	female	34	58	right	7
38 = jp107**	26	male	34	64	right	2
39 = jp108**	23	male	34	48	right	50*
40 = jp54**	26	male	n.a.	n.a.	left	2
41 = jp109**	24	female	31	69	left	4
42 = jp111**	22	female	31	57	left	3
43 = jp113**	21	female	33	56	left	4
44 = ct_b01	24	male	32	68	left	2
45 = jp116**	20	female	36	54	right	15
46 = jp112**	21	female	30	52	left	4

*Participant thus contributed less than 100 (out of 144) valid sentences. For participant-based statistics, these data were excluded from analyses.

**Participants that were included in comparions of *z* string “reading” data and normal reading data.

Appendix C

Experiment 2 (Z String "Reading"): Filler Sentences

1 Martina hasst den samstäglichen Einkauf zutiefst.
2 Der Virus auf der Festplatte führte zum Absturz des Computers.
3 Manche Studenten betrügen in Klausuren.
4 Der Verdächtige wohnte in einem Villenvorort von Oslo.
5 Statistisch gesehen ist die Wahrscheinlichkeit eines Attentates sehr gering.
6 Weiße Weihnachten gab es schon lange nicht mehr in Deutschland.
7 Der Alltag eines Säuglings besteht vorwiegend aus Schlafen und Essen.
8 Der Vorgesetzte wünscht in Ruhe gelassen zu werden.
9 Wenn man Blumen nicht gießt, vertrocknen sie schließlich.
10 Die Fußballer fuhren zum Auswärtsspiel nach Hamburg.
11 Ich weiß, was Du letzten Sommer getan hast.
12 Nach Ansicht der Schüler könnten die Ferien viel länger dauern.
13 Rot nennen viele Menschen als ihre Lieblingsfarbe.
14 Die alte Tapete mit den Mustern fanden die neuen Mieter unmodern.
15 Bitte fang nicht wieder an, über das Wetter zu jammern.
16 Die Prothese der alten Dame saß schlecht.
17 Nach einer Diät nehmen die meisten Menschen schnell wieder zu.
18 Wegen zu lauter Musik kam es zu Tumulten unter den Nachbarn.
19 Der Hund trottete missmutig durch den Wald.
20 Die Erde wird immer wärmer.
21 Lass uns Deinen Geburtstag mit einer kleinen Party feiern.
22 Neue Schuhe drücken oft unangenehm.
23 Auch Biobauern müssen ihre Pflanzen spritzen.
24 Die neue Chefin entpuppte sich als richtiges Biest.
25 Der Reporter stützte den betrunkenen Popstar.
26 So gesehen ist Monikas Baby ein wahrer Sonnenschein.
27 Von Aktien lass lieber die Finger, riet der Vater seiner Tochter.
28 Weltweit sterben noch immer zu viele Kinder an Unterernährung.
29 Die Mutter schimpfte, weil der Kühlschrank schon wieder leer war.
30 In der Ferne spielte ein Radio unbekannte Melodien.
31 Ohne Kaffee konnte Olaf nicht in den Tag starten.
32 Die Sekretärin war schon wieder krank.
33 Nimm doch bitte die Füße vom Tisch.
34 Heute ist ein wunderschöner Tag.
35 Der Bruder widmete sich mit Eifer dem Training.
36 Überall roch es nach frisch zubereitetem Fisch.

Appendix D

Experiment 3 (Reading with Salient OVP): Detailed Information on Participants

SUBJECT NUMBER	AGE	SEX	VOCABULARY	DIGIT SYMBOL	EYE DOMINANCE	MISSING SENTENCES
1	ca. 23	female	n.a.	n.a.	n.a.	29
2	28	male	31	60	left	4
3	20	female	31	62	right	0
4	26	female	32	82	left	5
5	23	female	29	64	left	66*
6	22	female	34	57	right	4
7	26	female	29	58	left	1
8	21	male	30	56	right	5
9	26	female	n.a.	n.a.	right	3
10	25	female	34	70	right	1
11	n.a.	n.a.	n.a.	n.a.	n.a.	16
12	21	female	n.a.	n.a.	n.a.	14
13	19	female	30	46	left	0
14	20	male	n.a.	n.a.	n.a.	0
15	26	female	29	47	right	0
16	28	male	35	53	left	0
17	24	male	31	44	right	2
18	22	female	28	70	left	7
19	24	female	35	59	left	2
20	22	female	29	67	right	4
21	22	female	33	55	left	0
22	27	female	35	53	right	2
23	26	male	32	60	right	0
24	24	male	n.a.	n.a.	n.a.	4
25	25	male	31	56	left	5
26	25	female	31	68	right	2
27	33	male	32	60	left	2
28	22	female	29	60	right	8
29	36	male	34	42	left	0
30	19	male	31	60	left	3
31	30	female	32	59	left	9
32	20	female	34	51	right	0
33	16	female	31	43	right	12
34	26	female	n.a.	n.a.	n.a.	1
35	22	female	33	63	right	3
36	15	female	29	44	right	1
37	29	female	33	61	right	2

*Participant thus contributed less than 100 (out of 144) valid sentences. For participant-based statistics, these data were excluded from analyses.

Appendix E

Experiment 3 (Reading with Salient OVP): Word Material – Potsdam Sentence Corpus

italics	target word 1
underlined	target word 2 (only for sentences 1-32)
red/bold/underlined	marked OVP letter

	target word length and frequency class
1 Den *Ton* gab der Küns**t**ler se**i**nem Geh**i**lfen.	short wl, high freq [1]
2 Der *Hof* lag w**e**it auße**r**halb des eigen**t**lichen Do**r**fes.	short wl, high freq [1]
3 Die Wan**d**erer sa**h**en R**e**he auf ei**n**er Lic**h**tung im *W**a**ld* ä**s**en.	short wl, high freq [1]
4 Den *Kopf* h**i**eb man fr**ü**her nur Mör**d**ern und Verr**ä**tern ab.	short wl, high freq [1]
5 Vorne am *Bug* sah man eine präc**h**tige Galio**n**sfigur.	short wl, low freq [2]
6 Sogar aus *R**a**ps* l**ä**ßt sich Kraft**s**toff herstellen.	short wl, low freq [2]
7 Torsten beoba**c**htete ges**t**ern eine Maus, die *E**f**eu* f**r**aß.	short wl, low freq [2]
8 Der schüc**h**terne kl**e**ine *G**n**om* m**i**ed die N**ä**he der El**f**en.	short wl, low freq [2]
9 Claudia ha**t**te ihr Fah**r**rad auf der *Straße* st**e**hen lassen.	medium wl, high freq [3]
10 Wir hä**t**ten sc**h**on vor ei**n**er *Stunde* wi**s**sen so**l**len, ob ihr kommt.	medium wl, high freq [3]
11 Die El**t**ern kon**n**ten ihre Kinder im *Ga**r**ten* ra**u**fen hören.	medium wl, high freq [3]
12 Er hä**t**te ni**c**ht a**u**ch noch am *Telefon* nör**g**eln so**l**len.	medium wl, high freq [3]
13 Wegen ih**r**er Diät ha**t**te die Gr**ä**fin le**i**der ke**i**ne *Au**s**ter* ne**h**men dürfen.	medium wl, low freq [4]
14 Die mei**s**ten *Ham**s**ter* ble**i**ben bei Tag in ih**r**em Häu**s**chen.	medium wl, low freq [4]
15 Man so**l**lte nie Ges**c**hirr mit einem drec**k**igen *La**p**pen* sp**ü**len mü**s**sen.	medium wl, low freq [4]
16 Man kann *Spa**r**gel* däm**p**fen oder in v**i**el Wasser ko**c**hen.	medium wl, low freq [4]
17 Manchmal sa**g**en *Opfer* vor Gericht ni**c**ht die vo**l**le Wah**r**heit.	medium wl, high freq [3]
18 Die mei**s**ten Befr**a**gten hö**r**en *Mu**s**ik* zur Entspannung.	medium wl, high freq [3]
19 Kinder es**s**en *Qu**a**rk* am lie**b**sten mit Früchten.	medium wl, high freq [3]
20 Bei Wö**l**fen le**b**en *Ru**d**el* ni**c**ht verwa**n**dter Tiere in getre**n**nten Rev**i**eren.	medium wl, high freq [3]
21 Die Fr**a**uen in den Anden**d**örfern we**b**en *St**o**ff* noch auf tradi**t**ionellen Webstühlen.	medium wl, low freq [4]
22 Die Platz**w**arte eb**n**en *St**ü**ck* für St**ü**ck den Rasen nach dem Spiel.	medium wl, low freq [4]
23 In den Fäs**s**ern gä**r**en *Be**i**ze* und La**u**ge.	medium wl, low freq [4]
24 Die För**s**ter kü**r**en *Ah**o**rn* zum B**a**um des Ja**h**res.	medium wl, low freq [4]
25 Wolfgangs Töc**h**ter stud**i**eren *Lite**r**atur* und Masch**i**nenbau.	long wl, high freq [5]
26 In der Klost**e**rschule herr**s**chen *Schw**e**ster* Ag**a**the und Schw**e**ster Ma**r**ia.	long wl, high freq [5]
27 Hier sch**e**inen *Kle**m**pner* am W**e**rk zu s**e**in.	long wl, high freq [5]
28 Im Aus**s**ehen gle**i**chen *Bra**t**sche* und Ge**i**ge s**i**ch sehr.	long wl, high freq [5]
29 Angeblich flu**n**kern *Kün**s**tler* oft bezü**g**lich ihrer Einn**a**hmen.	long wl, low freq [6]
30 Manchmal krak**e**elen *Poli**t**iker* genauso wie Demon**s**tranten.	long wl, low freq [6]
31 Die Ar**m**en plü**n**dern *Spe**i**cher* und Vorra**t**skeller der rei**c**hen Ba**u**ern.	long wl, low freq [6]
32 Die Ric**h**ter der Landw**i**rtschaftsschau präm**i**eren *Rhab**a**rber* und Man**g**old.	long wl, low freq [6]
33 Schon im**m**er war der Be**s**itz von *Land* sehr wic**h**tig.	short wl, high freq [1]
34 Ein berü**h**mter Ma**l**er hat s**i**ch se**l**bst ein *Ohr* abges**c**hnitten.	short wl, high freq [1]
35 Das Pferd ist se**i**nem Re**i**ter auf den *Fuß* get**r**eten.	short wl, high freq [1]
36 Kein ein**z**iges *Tor* f**i**el im gest**r**igen Sp**i**el.	short wl, high freq [1]
37 Der Ska**n**dal hat dem *Ruf* des Politikers deutlich gesc**h**adet.	short wl, high freq [1]
38 Als Kapit**a**lanlage ist *Gold* ni**c**ht zu empf**e**hlen.	short wl, high freq [1]
39 Markus kle**t**tert g**e**rn auf den al**t**en *Baum* im Ga**r**ten.	short wl, high freq [1]
40 Sarah hat ih**r**em Opa ein *Bild* ge**m**alt.	short wl, high freq [1]
41 Medizinisch ges**e**hen ist das *H**e**rz* ein Hohlm**u**skel.	short wl, high freq [1]
42 Jede Spr**a**che der *Welt* bes**i**tzt eine Gram**m**atik.	short wl, high freq [1]
43 Unsere *Kü**c**he* mü**ß**te dri**n**gend neu gestr**i**chen we**r**den.	medium wl, high freq [3]
44 Der Poli**t**iker reag**i**erte auf ke**i**ne *Frage* der Journ**a**listen.	medium wl, high freq [3]
45 Die *In**s**el* ist nur mit dem Flu**g**zeug zu erre**i**chen.	medium wl, high freq [3]

46	Es so**l**lte m**e**hr *St**r**om* mit Solar**e**nergie erz**e**ugt we**r**den.	medium wl, high freq [3]
47	Die mon**o**tone *Ar**b**eit* machte den Anges**t**ellten ke**i**nen Spaß.	medium wl, high freq [3]
48	In dem kle**i**nen *Zimmer* sta**n**den viel zu vi**e**le Möbel.	medium wl, high freq [3]
49	Das *Fen**s**ter* im Flur kl**e**mmt seit ein p**a**ar Tagen.	medium wl, high freq [3]
50	Die Sekre**t**ärin infor**m**ierte den *Kan**z**ler* e**r**st am näc**h**sten Morgen.	medium wl, high freq [3]
51	Vielleicht g**i**bt es b**a**ld im *Dez**e**mber* Oste**r**eier zu ka**u**fen.	long wl, high freq [5]
52	Das kl**e**ine Unter**n**ehmen ko**n**nte sich die te**u**re *Maschine* ni**c**ht lei**s**ten.	long wl, high freq [5]
53	Der *Fra**n**zose* ge**w**ann gegen den Bel**g**ier.	long wl, high freq [5]
54	Jan hat s**i**ch zum dri**t**ten mal die *Sch**u**lter* ausge**k**ugelt.	long wl, high freq [5]
55	Der Bis**c**hof ers**c**hien mit se**i**nem ne**u**en *Sek**r**etär* auf der Konferenz.	long wl, high freq [5]
56	Das *Schi**c**ksal* fü**h**rte die Fre**u**nde wi**e**der zusammen.	long wl, high freq [5]
57	Vor Ger**i**cht wu**r**de die *Situ**a**tion* nachg**e**stellt.	long wl, high freq [5]
58	Das We**t**ter im *Sept**e**mber* spi**e**lte ver**r**ückt.	long wl, high freq [5]
59	Die diesj**ä**hrige *Konf**e**renz* der Wisse**n**schaftler dau**e**rte v**i**er Tage.	long wl, high freq [5]
60	Der Hi**r**te wan**d**erte meh**r**ere *Kilometer* durch die Wü**s**te.	long wl, high freq [5]
61	Yvonne t**r**at unglü**c**klicherweise auf eine *Tube* Kleb**s**toff.	short wl, low freq [2]
62	Manuela rea**g**iert auf *S**e**nf* aller**g**isch.	short wl, low freq [2]
63	Martins gebro**c**hener *Zeh* sch**w**oll ra**s**ch an.	short wl, low freq [2]
64	Der alte Kap**i**tän goß st**e**ts ein we**n**ig *Rum* in se**i**nen Tee.	short wl, low freq [2]
65	Die sch**m**ale *Öse* ist zu kl**e**in für den Fa**d**en.	short wl, low freq [2]
66	Die Tä**n**zer pro**b**ten i**h**re *Kür* beso**n**ders int**e**nsiv.	short wl, low freq [2]
67	Nach dem St**r**eit sc**h**ien al**l**es wi**e**der im *Lot* zu sein.	short wl, low freq [2]
68	Der fr**i**sch gek**o**chte *Brei* war n**o**ch zu heiß.	short wl, low freq [2]
69	Die Schne**i**derin ste**c**kte die *Naht* sorgf**ä**ltig ab.	short wl, low freq [2]
70	Auf dem höc**h**sten *M**a**st* hi**e**lt der Pi**r**at Wa**c**he.	short wl, low freq [2]
71	Claudia k**a**nn Salat**s**aucen mit v**i**el *Essig* ni**c**ht auss**t**ehen.	medium wl, low freq [4]
72	Die *To**r**te* er**w**ies s**i**ch als ein wa**h**rer Lecke**r**bissen.	medium wl, low freq [4]
73	Sie mac**h**ten ei**n**en Spaziergang am *De**i**ch* entlang.	medium wl, low freq [4]
74	Ulf hat sc**h**on wi**e**der eine *Ni**e**te* gez**o**gen.	medium wl, low freq [4]
75	Der *Gi**e**bel* des al**t**en Hauses dr**o**hte einzu**s**türzen.	medium wl, low freq [4]
76	Das Karam**e**llbonbon bl**i**eb Ju**l**ia am *Ga**u**men* kleben.	medium wl, low freq [4]
77	Tamara fü**h**rte mit der *Heb**a**mme* meh**r**ere Gespräche.	medium wl, low freq [4]
78	Nach der Tra**u**ung war**t**ete eine *Kut**s**che* vor der Ki**r**che.	medium wl, low freq [4]
79	Robert l**i**eß s**i**ch den *Sch**i**nken* in Sch**e**iben schn**e**iden.	long wl, low freq [6]
80	Die Kinder hüp**f**ten auf der al**t**en *Mat**r**atze* he**r**um.	long wl, low freq [6]
81	Laura ste**l**lte eine *Sch**ü**ssel* Kir**s**chen auf den Tisch.	long wl, low freq [6]
82	Das entsc**h**eidende *Tele**f**onat* verzö**g**erte s**i**ch.	long wl, low freq [6]
83	Mandy aß die *Mand**a**rine* so**f**ort auf.	long wl, low freq [6]
84	Der Tep**p**ich mit dem *Schn**ö**rkel* ge**f**iel Bet**t**ina ni**c**ht.	long wl, low freq [6]
85	Der majes**t**ätische *Glet**s**cher* wu**r**de schon oft best**i**egen.	long wl, low freq [6]
86	Der Groß**v**ater fand in se**i**nem *Pant**o**ffel* eine Wäsch**e**klammer.	long wl, low freq [6]
87	Johannes wo**l**lte unbe**d**ingt *Karu**s**sell* fa**h**ren.	long wl, low freq [6]
88	Die *Olym**p**iade* fi**n**det di**e**ses Jahr in Austr**a**lien st**a**tt.	long wl, low freq [6]
89	Sonja *kam* als Ein**z**ige pünk**t**lich.	short wl, high freq [1]
90	Der alte Mann *zog* ei**n**en Ka**r**ren zum Markt**p**latz.	short wl, high freq [1]
91	Keiner wu**ß**te, was zu *tun* war.	short wl, high freq [1]
92	Heute mo**r**gen *saß* auf uns**e**rer Ter**r**asse ein Fr**o**sch.	short wl, high freq [1]
93	Der Wande**r**smann *bat* den Wirt um et**w**as Wa**s**ser.	short wl, high freq [1]
94	Seit ges**t**ern *g**e**ht* es dem Pati**e**nten deu**t**lich besser.	short wl, high freq [1]
95	Der Waffe**n**stillstand *h**ä**lt* s**e**it f**a**st v**i**er Mon**a**ten.	short wl, high freq [1]
96	Freundlich zu *s**e**in* k**a**nn nie sch**a**den.	short wl, high freq [1]
97	Die Mu**t**ter *g**i**bt* ih**r**en Kindern je**d**en Mo**n**tag Tasch**e**ngeld.	short wl, high freq [1]
98	Jeder Vors**c**hlag *g**i**lt*, der recht**z**eitig einge**r**eicht w**i**rd.	short wl, high freq [1]
99	Ich weiß ni**c**ht, ob wir uns noch *se**h**en* werden.	medium wl, high freq [3]
100	Die mei**s**ten Kinder *gehen* ge**r**ne zur Schule.	medium wl, high freq [3]
101	Viele Kinder *le**s**en* nur n**o**ch se**l**ten.	medium wl, high freq [3]

102 Die Journ**a**listen *fr**a**gen* den Bürge**r**meister nach se**i**ner Meinung. medium wl, high freq [3]
103 Kevin und Ma**r**ie *spi**e**len* oft im Ga**r**ten. medium wl, high freq [3]
104 Die Gesch**w**orenen *gla**u**ben* dem Bekl**a**gten bes**t**immt al**l**es. medium wl, high freq [3]
105 Am be**s**ten *ste**l**len* wir das Klavier nicht di**r**ekt ans Fenster. medium wl, high freq [3]
106 Meistens *wün**s**chen* Ki**n**der sich Spie**l**zeug zu Weihn**a**chten. long wl, high freq [5]
107 Einige Häft**l**inge *spr**e**chen* nicht gern mitei**n**ander. long wl, high freq [5]
108 Nur we**n**ige Menschen *brauchen* ein Ha**n**dy wir**k**lich. long wl, high freq [5]
109 Einige der Anges**t**ellten *arb**e**iten* nur vormittags. long wl, high freq [5]
110 Die Spi**e**ler ho**f**fen, daß sie i**h**re Ge**g**ner *sch**l**agen* we**r**den. long wl, high freq [5]
111 Ich bin ni**c**ht sicher, ob a**l**le die Prüfung *sch**a**ffen* we**r**den. long wl, high freq [5]
112 Die mei**s**ten Geschäfte *schließen* sam**s**tags fr**ü**her als un**t**er der Woche. long wl, high freq [5]
113 Die Astro**n**auten *antw**o**rten* s**e**it Tagen ni**c**ht mehr. long wl, high freq [5]
114 Die Sch**ü**ler *schr**e**iben* ih**r**er kra**n**ken Leh**r**erin ei**n**en Brief. long wl, high freq [5]
115 Die Besch**u**ldigten *schw**e**igen* zu den Vorwürfen. long wl, high freq [5]
116 Die be**i**den Mäd**c**hen *schü**t**teln* sich vor lachen. long wl, high freq [5]
117 Dorothea *log* oft bei Fr**a**gen nach ih**r**em Alter. short wl, low freq [2]
118 Die Großmutter *wog* die Zut**a**ten beim Backen s**e**hr ge**n**au. short wl, low freq [2]
119 Die Mutter sa**g**te, N**i**na *übe* ge**r**ade Kla**v**ier. short wl, low freq [2]
120 Der Geh**i**lfe des Gär**t**ners *sät* Kr**e**sse und Radie**s**chen. short wl, low freq [2]
121 Die zwei Nic**h**ten *ö**d**en* sich gegen**s**eitig an. short wl, low freq [2]
122 Sei so gut und *miß* bi**t**te die Ti**e**fe des Re**g**als. short wl, low freq [2]
123 Jetzt *r**a**te* d**o**ch mal, wen ich ges**e**hen h**a**be! short wl, low freq [2]
124 Sei so l**i**eb und *l**i**es* mir die Ang**a**ben vor! short wl, low freq [2]
125 Bitte *w**i**rf* den Ball nicht wi**e**der a**u**fs Dach. short wl, low freq [2]
126 Bitte *hi**l**f* de**i**ner Schwester beim Aufr**ä**umen. short wl, low freq [2]
127 Die strei**k**enden Fa**h**rer ko**n**nte man kilom**e**terweit *hu**p**en* hö**r**en. medium wl, low freq [4]
128 Die Gär**t**ner *mä**h**en* den Ra**s**en im P**a**rk je**d**en Mittwoch. medium wl, low freq [4]
129 Gute Beziehungen *eb**n**en* vi**e**len Unter**n**ehmern den Weg zum Er**f**olg. medium wl, low freq [4]
130 Mäuse und Ra**t**ten *na**g**en* ge**r**ne an Strom**k**abeln. medium wl, low freq [4]
131 Tierärzte *im**p**fen* ke**i**ne Kani**n**chen ge**g**en Tol**l**wut. medium wl, low freq [4]
132 Die Hu**n**de der Wäc**h**ter *be**l**len* beim gerin**g**sten An**l**aß. medium wl, low freq [4]
133 Affen *kra**u**len* sich oft stund**e**nlang das Fell. medium wl, low freq [4]
134 Die For**s**cher *sta**p**fen* du**r**ch den Sc**h**nee zu**r**ück zum Lager. medium wl, low freq [4]
135 Viele Ba**b**ys *sch**i**elen* nach der Geburt eine We**i**le lang. long wl, low freq [6]
136 Die Bä**u**me in den Wäldern *spei**c**hern* sehr v**i**el Wasser. long wl, low freq [6]
137 Die meisten Le**u**te *schu**m**meln* beim Spi**e**len geleg**e**ntlich. long wl, low freq [6]
138 Nach dem Sp**i**el *mass**i**eren* die Thera**p**euten den Spi**e**lern die Be**i**ne. long wl, low freq [6]
139 Die be**i**den Mäd**c**hen *tus**c**heln* wäh**r**end des Unter**r**ichts. long wl, low freq [6]
140 Die Hä**u**ser am Hor**i**zont *fli**m**mern* in der Sonne. long wl, low freq [6]
141 Den ga**n**zen Tag über ko**n**nte man die Ra**b**en *krä**c**hzen* hören. long wl, low freq [6]
142 Vor dem Auf**t**ritt *schm**i**nken* die Schau**s**pieler s**i**ch. long wl, low freq [6]
143 Die zwei fre**c**hen Ju**n**gs *heu**c**heln* Uns**c**huld. long wl, low freq [6]
144 Manche Men**s**chen *sto**t**tern* bei Nervo**s**ität. long wl, low freq [6]

Appendix F

Experiment 4 (Reading with a Bite Bar): Detailed Information on Participants

SUBJECT NUMBER	AGE	SEX	VOCABULARY	DIGIT SYMBOL	EYE DOMINANCE	MISSING SENTENCES
1	19	male	29	62		2
2	17	female	27	57		11
3	19	male	30	65		1
4	16	female	32	60		9
5	16	female	29	75		9
6	18	female	29	80		5
7	17	female	29	57		9
8	19	female	32	74		1
9	18	male	33	57		18
10	26	female	33	80		10
11	17	male	28	62		13
12	19	female	33	57		8
13	17	male	31	41		24
14	17	female	31	73		10
15	16	female	29	59		32
16	17	male	32	58		0
17	21	male	29	50		0
18	19	female	31	61		5
19	17	female	34	57		13
20	19	male	35	74		14
21	18	female	32	64		10
22	20	female	31	77		0
23	19	female	32	66		3
24	17	male	29	56		26
25	17	male	27	58		18
26	19	female	27	69		9
27	17	male	33	64		10
28	16	female	31	49		8
29	17	female	29	53		38
30	18	male	31	63		7
31	17	male	27	56		1

Appendix G

Experiment 5 (Reading under Low Contrast): Detailed Information on Participants

SUBJECT NUMBER	AGE	SEX	VOCABULARY	DIGIT SYMBOL	EYE DOMINANCE	MISSING SENTENCES
1	23	female	36	78	left	35
2	24	female	33	58	right	9
3	21	female	30	59	right	7
4	21	female	34	68	right	6
5	21	female	32	59	left	5
6	21	female	31	51	left	42
7	21	female	26	57	left	17
8	21	female	29	60	right	6
9	27	male	32	43	n.a.	2
10	21	female	32	59	n.a.	25
11	22	female	n.a.	n.a.	right	1
12	22	female	30	68	n.a.	0
13	24	female	31	50	right	27
14	25	female	29	58	n.a.	6
15	25	female	27	52	n.a.	45*
16	22	male	29	63	right	1
17	22	female	27	74	left	7
18	20	female	31	72	n.a.	2
19	21	female	30	76	left	54*
20	20	female	n.a.	n.a.	n.a.	7
21	25	female	34	62	left	2
22	28	female	32	51	left	35
23	19	female	31	58	right	6
24	30	female	35	57	right	53*
25	20	female	32	47	n.a.	4
26	29	female	n.a.	n.a.	left	3
27	22	male	32	53	n.a.	19
28	20	female	31	59	right	0
29	24	female	33	62	n.a.	2
30	18	female	36	69	left	66*

* Participant thus contributed less than 100 (out of 144) valid sentences. For participant-based statistics, these data were excluded from analyses.

Appendix H

Experiment 6 (Reading with Recurrent Sentence Shifts): Detailed Information on Participants

Table H1 Experiment 6 – reading with recurrent sentence shifts. Detailed information on participants.

SUBJECT NUMBER	AGE	SEX	VOCABULARY	DIGIT SYMBOL	EYE DOMINANCE	MISSING SENTENCES
1	21	female	31	66	right	2
2	22	female	24	69	left	10
3	21	female	34	67	right	0
4	24	female	28	59	right	1
5	24	female	34	58	right	4
6	26	female	35	75	right	8
7	24	male	32	54	right	2
8	30	female	27	48	left	1
9	24	male	35	62	right	2
10	20	female	29	28	right	10
11	20	female	28	64	right	14
12	27	female	28	59	right	1
13	21	female	31	64	right	2
14	24	female	32	60	right	13
15	19	n.a.	n.a.	n.a.	n.a.	2
16	22	female	32	61	left	5
17	26	female	33	58	right	33
18	21	n.a.	n.a.	n.a.	n.a.	1
19	22	female	34	58	right	0
20	24	female	32	65	right	4
21	21	male	33	56	right	2
22	51	female	33	54	right	42
23	23	female	30	49	right	7
24	26	male	33	63	right	4
25	20	female	31	60	right	3
26	22	male	33	64	left	6
27	22	female	34	56	right	0
28	20	male	27	54	left	2
29	22	female	31	54	right	2
30	28	female	33	56	left	3
31	21	female	35	58	right	0
32	25	female	31	54	right	27
33	24	female	32	47	right	24
34	21	female	33	61	right	2
35	23	female	33	50	right	3
36	24	male	33	53	left	1
37	21	male	31	60	left	2
38	20	female	34	64	right	0
39	19	female	31	36	right	16
40	21	female	33	74	right	3
41	23	female	32	65	right	1
42	24	male	n.a.	n.a.	left	0
43	23	female	34	38	left	5
44	21	female	26	55	left	12
45	22	female	32	67	right	3
46	23	female	33	70	left	13
47	21	female	31	58	right	0

Table H2 Experiment 6 – reading with recurrent sentence shifts. Participant-based information on saccade-contingent sentence shifts.

I	II	III	IV	V	VI	VII
1	1965	694	35.32	92.07	3.05	
2	1961	681	34.73	89.72	4.52	
3	1217	467	38.37	94.86	4.2	
4	1220	493	40.41	99.19	3.02	
5	1020	397	38.92	98.99	3	
6	1009	368	36.47	96.47	4.38	
7	1634	634	38.80	93.38	4.24	
8	1189	441	37.09	91.61	4.14	
9	837	294	35.13	98.98	4.38	
10	1647	629	38.19	92.37	4.23	
11	900	317	35.22	98.74	4.45	
12	1392	530	38.07	95.28	4.39	
13	1450	557	38.41	90.84	4.28	
14	1289	475	36.85	94.32	4.39	
15	1224	472	38.56	95.13	4.37	
16	1131	431	38.11	99.07	4.21	
17	977	339	34.70	95.87	4.54	
18	1199	456	38.03	95.18	4.52	
19	1248	508	40.71	99.41	3.04	
20	1475	592	40.14	93.24	3.02	+
21	1161	435	37.47	94.25	4.21	
22	1395	517	37.06	96.52	4.26	
23	1084	401	36.99	99.5	4.19	
24	1468	569	38.76	93.85	4.5	
25	1003	373	37.19	98.93	4.61	
26	1996	697	34.92	94.4	3.06	
27	1184	469	39.61	97.23	3.02	
28	1653	602	36.42	92.03	4.37	
29	1043	392	37.58	98.72	4.28	
30	1551	600	38.68	94.67	4.26	
31	1278	516	40.38	95.93	3.05	+
32	1334	549	41.15	96.54	3.09	
33	993	370	37.26	99.19	4.5	
34	1417	576	40.65	96.01	3	
35	1735	635	36.60	97.48	3.01	
36	1103	427	38.71	98.13	3	
37	1634	619	37.88	94.18	4.23	
38	927	338	36.46	99.11	4.5	
39	1467	578	39.40	94.81	4.4	
40	1152	439	38.11	97.95	4.35	+
41	1084	406	37.45	99.01	4.38	
42	1430	555	38.81	94.05	4.39	+
43	1115	417	37.40	95.92	4.21	
44	1528	598	39.14	93.31	4.72	
45	1231	471	38.26	97.45	4.25	
46	1072	424	39.55	96.93	3.02	
47	1236	468	37.86	96.15	4.98	

I	running subject number
II	number of online detected saccades
III	valid number of displacement saccades (excluding displacements during saccade to the lower right corner
IV	percentage of valid displacement saccades (relative to all online detected saccades)
V	percentage of valid displacements that were not seen by the subject
VI	mean delay of the SR Research EyeLink II system [ms]
VII	+ if subject reported to have noticed some sentence displacements

Appendix I

Tables Belonging to Chapter 2.2, Global Analyses of Experiment 2, “Benchmark Plots”

– Word-Based Descriptive Statistics, Statistical Analyses –

Table I1 Experiment 2 – *z* string “reading” (Exp) vs. normal reading control data (Con). Means and standard deviations of four duration measures, and four probability measures as a function of word length.

			Word Length											**N**
			2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	
FirstFd	**Mean**	**Exp**	214	226	238	228	232	225	238	235	227	236	229	13
		Con	181	197	186	197	190	196	202	198	209	203	196	14
	Sd	**Exp**	58.6	34.7	43.7	40.5	43.7	35.9	44.9	44.7	53.3	46.4	37.5	13
		Con	35.7	51.2	32.7	27.2	29	29.8	28.6	23.2	25.8	28.2	28	14
SecFd	**Mean**	**Exp**	237	204	212	209	213	213	212	209	204	212	216	13
		Con	172	173	164	175	168	162	171	161	165	170	168	13
	Sd	**Exp**	68.3	61.2	51.8	48.4	45.8	56.8	51.7	57.9	58	59.6	53.6	13
		Con	63.4	53.7	44.8	26.9	33.3	26.8	28	24.4	44.9	36.3	33	13
SFd	**Mean**	**Exp**	235	242	251	251	251	254	257	267	262	254	229	29
		Con	215	206	204	209	197	199	213	216	212	221	215	30
	Sd	**Exp**	48.8	52	61.8	65.7	61.8	66.1	69.2	73.5	83	69.9	49.3	29
		Con	42	28.9	24.6	27.6	26.8	26.5	31.4	30.2	39.8	45.8	42.6	30
Time$_{\text{Total}}$	**Mean**	**Exp**	241	258	274	280	288	301	311	334	331	371	408	31
		Con	220	225	231	253	232	241	279	287	328	339	406	31
	Sd	**Exp**	54.6	63.3	77.3	89.4	89.6	102	114.1	139.6	124.5	156.8	178.9	31
		Con	37.4	36.4	38.3	38.6	37.5	35.2	52.7	55.2	76	87.4	101.1	31
p_{Skip}	**Mean**	**Exp**	0.54	0.4	0.3	0.24	0.19	0.15	0.13	0.11	0.09	0.08	0.05	31
		Con	0.56	0.41	0.23	0.14	0.11	0.07	0.04	0.02	0.02	0.01	0.01	31
	Sd	**Exp**	0.22	0.22	0.23	0.22	0.19	0.17	0.14	0.13	0.12	0.11	0.07	31
		Con	0.2	0.17	0.13	0.09	0.08	0.06	0.04	0.02	0.05	0.02	0.03	31
p_2	**Mean**	**Exp**	0.02	0.05	0.08	0.11	0.13	0.17	0.19	0.21	0.25	0.28	0.29	31
		Con	0.02	0.04	0.07	0.1	0.09	0.14	0.21	0.26	0.33	0.34	0.39	31
	Sd	**Exp**	0.03	0.06	0.1	0.12	0.13	0.14	0.14	0.13	0.19	0.16	0.17	31
		Con	0.03	0.03	0.05	0.06	0.05	0.08	0.11	0.14	0.19	0.17	0.15	31
p_3	**Mean**	**Exp**	0	0	0	0.01	0.01	0.02	0.03	0.05	0.05	0.1	0.16	31
		Con	0	0	0.01	0.01	0.01	0.01	0.03	0.04	0.1	0.1	0.24	31
	Sd	**Exp**	0	0	0.01	0.02	0.02	0.04	0.06	0.11	0.09	0.16	0.2	31
		Con	0.01	0	0.01	0.01	0.01	0.01	0.03	0.04	0.12	0.12	0.15	31
p_{Regr}	**Mean**	**Exp**	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0	0.02	0.01	31
		Con	0.08	0.08	0.08	0.07	0.04	0.05	0.05	0.03	0.02	0.05	0.05	31
	Sd	**Exp**	0.04	0.03	0.02	0.03	0.02	0.02	0.01	0.02	0	0.03	0.02	31
		Con	0.09	0.07	0.06	0.04	0.03	0.03	0.04	0.04	0.04	0.08	0.05	31

Table I2 Experiment 2 – *z* string “reading” vs. normal reading control data. Means and standard deviations of four duration measures, and four probability measures as a function of word frequency.

		Mindless Reading						**Normal Reading**					
		Word Frequency					**N**	**Word Frequency**					**N**
		1 Low	**2**	**3**	**4**	**5 High**		**1 Low**	**2**	**3**	**4**	**5 High**	
FirstFd	Mean	229	230	236	220	237	22	201	192	197	185	187	24
	Sd	33.1	33.7	35	39.5	52.1	22	22.4	22.2	27	28.2	45.8	24
SecFd	Mean	207	213	209	203	224	22	173	160	169	173	180	23
	Sd	46.6	48.5	49.4	56.9	76.3	22	24.3	26.8	24.5	41.1	62.7	23
SFD	Mean	254	252	253	243	237	31	215	199	203	207	200	31
	Sd	66.1	62.6	60.7	52.8	50	31	28.1	25.4	27.3	29.5	30.1	31
$\mathbf{TIME}_{\mathbf{Total}}$	Mean	311	305	289	263	253	31	294	249	239	227	220	31
	Sd	107.2	104.2	88.4	65.6	59.2	31	52	40.6	37.2	37.7	34.9	31
p_{Skip}	Mean	0.18	0.17	0.24	0.38	0.46	31	0.08	0.11	0.17	0.36	0.5	31
	Sd	0.16	0.17	0.19	0.22	0.22	31	0.05	0.07	0.08	0.18	0.19	31
p_{2}	Mean	0.16	0.17	0.12	0.06	0.04	31	0.2	0.15	0.1	0.05	0.03	31
	Sd	0.11	0.12	0.12	0.06	0.05	31	0.08	0.07	0.06	0.04	0.03	31
p_{3+}	Mean	0.04	0.03	0.01	0.01	0	31	0.05	0.02	0.01	0.01	0	31
	Sd	0.06	0.05	0.02	0.01	0	31	0.04	0.02	0.01	0.01	0.01	31
p_{Regr}	Mean	0.01	0.01	0.01	0.02	0.03	31	0.06	0.04	0.06	0.08	0.08	31
	Sd	0.02	0.02	0.02	0.03	0.04	31	0.03	0.03	0.04	0.07	0.09	31

Table I3 Experiment 2 – *z* string "reading" vs. normal reading control data. Statistical analyses of four duration measures, and four probability measures. For each measure, a 2 (experimental vs. control data) × 5 (frequency classes), and/or a 2 (experimental vs. control data) × 11 (word length) repeated measures ANOVA was employed. $^{*}p < .05$.

	Exp				**Word Length**				**Exp × Word Length**			
	Mse	**F (1,45)**	**p**	**η^2**	**Mse**	**F (10,36)**	**p**	**η^2**	**Mse**	**F (10,36)**	**p**	**η^2**
FirstFd	1372.170	11.126	**.016***	.650	2594.511	1.501	.247	.200	2263.607	1.765	.179	.227
SecFd	4084.108	19.205	**.007***	.793	5767.212	.513	.658	.093	7626.358	.546	.619	.098
Sfd	11306.750	11.043	**.003***	.306	1373.743	4.573	**.002***	.155	997.698	2.656	**.035***	.096
Time$_{\text{Total}}$	66621.026	2.671	.113	.082	8689.098	88.990	**.000***	.748	8141.528	3.050	**.048***	.092
P_{Skip}	.115	5.336	**.028***	.151	.045	193.933	**.000***	.866	.017	5.418	**.003***	.153
P_2	.061	1.015	.322	.033	.027	79.939	**.000***	.727	.015	5.220	**.000***	.148
P_{3+}	.026	.586	.450	.019	.025	48.079	**.000***	.616	.023	2.426	.098	.075
P_{Regr}	.006	46.497	**.000***	.608	.005	8.095	**.000***	.212	.003	2.673	**.039***	.082

	Exp				**Word Frequency**				**Exp × Word Frequency**			
	Mse	**F (1,45)**	**p**	**η^2**	**Mse**	**F (4,42)**	**p**	**η^2**	**Mse**	**F (4,42)**	**p**	**η^2**
FirstFd	1965.033	38.641	**.000***	.682	992.416	1.358	.270	.070	1838.355	.594	.533	.032
SecFd	4172.095	13.069	**.002***	.435	2092.280	.576	.565	.033	2337.190	.110	.885	.006
Sfd	8376.126	17.155	**.000***	.364	488.934	9.860	**.000***	.247	224.334	6.267	**.001***	.173
Time$_{\text{Total}}$	18802.201	6.052	**.020***	.168	1688.738	73.026	**.000***	.709	1242.475	7.842	**.003***	.207
P_{Skip}	.078	1.763	.194	.056	.022	184.286	**.000***	.860	.008	13.373	**.000***	.308
P_2	.023	.063	.803	.002	.005	111.654	**.000***	.788	.002	6.743	**.002***	.184
P_{3+}	.002	.066	.799	.002	.001	37.106	**.000***	.553	.002	1.405	.251	.045
P_{Regr}	.004	43.869	**.000***	.594	.003	5.743	**.013***	.161	.002	1.857	.173	.058

Appendix J

Tables Belonging to Chapter 2.3, Global Analyses of Experiment 3, “Benchmark Plots”

– Word-Based Descriptive Statistics, Statistical Analyses –

Table J1 Experiment 3 – reading with salient OVP vs. normal reading control data. Means and standard deviations of four duration measures, and four probability measures as a function of word frequency.

		Reading With Salient Ovp						**Normal Reading**					
		Word Frequency					**N**	**Word Frequency**					**N**
		1 **Low**	**2**	**3**	**4**	**5** **High**		**1** **Low**	**2**	**3**	**4**	**5** **High**	
FirstFd	Mean	207	195	195	190	215	27	198	191	192	185	193	77
	Sd	26.9	21.7	24.3	30.3	71.6	27	30.3	30.8	35.8	31.2	55.3	77
SecFd	Mean	184	168	180	176	186	27	168	160	164	167	170	77
	Sd	26.8	23.8	27.1	37.3	64.7	27	27.7	30.7	33.2	39.9	108.1	77
Sfd	Mean	227	210	212	217	214	36	210	195	199	201	199	107
	Sd	33.4	25.1	25.5	30.6	36.9	36	34.2	29.9	30.4	32.8	34.8	107
$\text{Time}_{\text{Total}}$	Mean	317	268	254	241	236	36	275	238	228	217	210	107
	Sd	68.8	53.2	41.4	44.7	46.9	36	62.8	46.4	41.2	39.8	41.3	107
p_{Skip}	Mean	0.09	0.13	0.17	0.37	0.54	36	0.09	0.12	0.18	0.39	0.54	107
	Sd	0.05	0.07	0.11	0.16	0.14	36	0.05	0.07	0.1	0.17	0.16	107
p_2	Mean	0.22	0.17	0.12	0.07	0.04	36	0.18	0.14	0.09	0.05	0.03	107
	Sd	0.08	0.08	0.05	0.05	0.05	36	0.08	0.07	0.06	0.04	0.04	107
p_{3+}	Mean	0.06	0.03	0.01	0.01	0	36	0.04	0.02	0.01	0	0	107
	Sd	0.04	0.03	0.01	0.01	0.02	36	0.04	0.02	0.01	0.01	0.01	107
p_{Regr}	Mean	0.07	0.06	0.06	0.09	0.11	36	0.05	0.04	0.05	0.06	0.07	107
	Sd	0.05	0.04	0.05	0.07	0.09	36	0.03	0.03	0.04	0.06	0.07	107

Table J2 Experiment 3 – reading with salient OVP (Exp) vs. normal reading control data (Con). Means and standard deviations of four duration measures, and four probability measures as a function of word length.

			Word Length											
			2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**N**
FirstFd	**Mean**	**Exp**	202	204	192	200	196	194	198	205	205	207	204	25
		Con	185	192	193	197	192	193	198	193	198	200	195	53
	Sd	**Exp**	52.6	36.6	32.4	29.8	32.4	25.9	27.9	29.1	47.2	36.6	25.9	25
		Con	43.3	42.9	44.5	36	37.9	40	43.8	33.7	42.9	36.5	29.7	53
SecFd	**Mean**	**Exp**	180	184	182	185	178	170	178	170	189	181	184	25
		Con	167	166	162	170	164	159	162	161	166	170	166	52
	Sd	**Exp**	64.9	49.5	27.8	33.6	27.4	29.9	30.2	24.7	49	28	42.3	25
		Con	61.3	50.6	45	37.6	43.7	31.7	35.1	33.8	47.1	39.5	33.2	52
Sfd	**Mean**	**Exp**	220	214	216	219	209	211	218	227	233	222	231	32
		Con	207	201	201	204	193	194	209	212	205	216	205	103
	Sd	**Exp**	38	32.4	28.6	28	25.2	26.6	25.9	34.2	57.8	32.4	55.3	32
		Con	40.1	32.7	29.9	31.1	30.5	31.3	36.5	35.6	36.7	41.8	40.3	103
Time$_{Total}$	**Mean**	**Exp**	223	239	248	267	250	263	299	313	356	363	439	36
		Con	211	215	221	238	222	229	259	273	293	319	379	107
	Sd	**Exp**	41.9	45.5	41.6	47.5	42.4	55.4	69.4	74.5	97.3	111.3	104.6	36
		Con	43.6	39.9	39.8	42.9	41.9	47.1	59.3	70	76.9	87.8	106.5	107
p_{Skip}	**Mean**	**Exp**	0.59	0.43	0.22	0.15	0.12	0.09	0.05	0.03	0.04	0.02	0.01	36
		Con	0.59	0.44	0.25	0.16	0.12	0.08	0.04	0.02	0.01	0	0	107
	Sd	**Exp**	0.15	0.15	0.13	0.12	0.09	0.06	0.04	0.04	0.06	0.04	0.03	36
		Con	0.17	0.16	0.14	0.11	0.09	0.06	0.04	0.02	0.04	0.01	0.01	107
p_2	**Mean**	**Exp**	0.04	0.05	0.09	0.13	0.13	0.17	0.25	0.28	0.32	0.35	0.39	36
		Con	0.02	0.04	0.06	0.09	0.1	0.12	0.18	0.24	0.31	0.34	0.4	107
	Sd	**Exp**	0.05	0.05	0.05	0.05	0.06	0.08	0.12	0.15	0.17	0.16	0.12	36
		Con	0.04	0.04	0.04	0.06	0.06	0.07	0.11	0.14	0.2	0.18	0.14	107
p_3	**Mean**	**Exp**	0	0	0.01	0.01	0.02	0.02	0.04	0.05	0.13	0.13	0.24	36
		Con	0	0	0	0.01	0.01	0.01	0.02	0.04	0.06	0.09	0.21	107
	Sd	**Exp**	0.01	0.01	0.01	0.01	0.02	0.03	0.05	0.05	0.12	0.13	0.17	36
		Con	0	0	0.01	0.01	0.01	0.01	0.03	0.04	0.09	0.11	0.17	107
p_{Regr}	**Mean**	**Exp**	0.1	0.1	0.08	0.08	0.05	0.05	0.07	0.06	0.04	0.06	0.05	36
		Con	0.07	0.07	0.06	0.06	0.04	0.04	0.04	0.03	0.02	0.04	0.03	107
	Sd	**Exp**	0.08	0.07	0.07	0.06	0.05	0.04	0.05	0.07	0.05	0.08	0.06	36
		Con	0.07	0.06	0.05	0.04	0.03	0.03	0.03	0.04	0.04	0.05	0.05	107

Table J3 Experiment 3 – reading with salient OVP vs. normal reading control data. Statistical analyses of four duration measures, and four probability measures. For each measure, an ANOVA with "experimental condition" (reading with salient OVP vs. normal reading) as between-subject factor and "word frequency" and/or "word length" as the respective within-subject factor was employed. * $p < .05$.

	Exp				**Word Frequency**				**Exp × Word Frequency**			
	MSE	**F (1,141)**	**p**	**η^2**	**MSE**	**F (4,138)**	**p**	**η^2**	**MS**	**F (4,138)**	**p**	**η^2**
FirstFd	4119.954	2.167	.144	.021	1845.049	4.301	**.021***	.041	3054.557	1.656	.198	.016
SecFd	6072.032	2.643	.107	.026	5791.726	1.287	.271	.013	670.846	.116	.811	.001
SFD	4488.075	6.628	**.011***	.045	279.067	26.308	**.000***	.157	106.074	.380	.713	.003
Time$_{Total}$	10049.726	11.965	**.001***	.078	854.161	222.944	**.000***	.613	3255.553	3.811	**.025***	.026
p_{Skip}	.045	.060	.806	.000	.014	683.851	**.000***	.829	.006	.418	.622	.003
p_2	.012	7.522	**.007***	.051	.003	331.882	**.000***	.702	.008	2.456	.091	.017
p_{3+}	.001	7.162	**.008***	.048	.001	138.261	**.000***	.495	.004	4.421	**.020***	.030
p_{Regr}	.009	7.503	**.007***	.051	.003	23.367	**.000***	.142	.004	1.411	.246	.010
	Exp				**Word Length**				**Exp × Word Length**			
	MSE	**F (1,141)**	**p**	**η^2**	**MSE**	**F (10,132)**	**p**	**η^2**	**MS**	**F (10,132)**	**p**	**η^2**
FirstFd	7788.811	1.641	.204	.023	951.424	2.343	**.027***	.032	1437.430	1.511	.168	.021
SecFd	6941.745	6.555	**.013***	.088	1976.885	1.926	.083	.028	1167.538	.591	.721	.009
SFD	8415.858	4.133	**.044***	.031	736.940	11.394	**.000***	.080	1166.617	1.583	.170	.012
Time$_{Total}$	34576.317	11.338	**.001***	.074	5366.811	301.201	**.000***	.681	26411.376	4.921	**.005***	.034
p_{Skip}	.044	.006	.938	.000	.025	690.635	**.000***	.830	.030	1.199	.306	.008
p_2	.055	3.678	.057	.025	.022	217.310	**.000***	.606	.028	1.311	.267	.009
p_{3+}	.016	5.886	**.017***	.040	.021	132.489	**.000***	.484	.064	3.034	.055	.021
p_{Regr}	.013	9.172	**.003***	.061	.003	23.028	**.000***	.140	.002	.661	.650	.005

Appendix K

Tables Belonging to Chapter 2.4, Global Analyses of Experiment 4, “Benchmark Plots” – Word-Based Descriptive Statistics, Statistical Analyses –

Table K1 Experiment 4 – reading with a bite bar vs. chin rest reading data. Means and standard deviations of four duration measures, and four probability measures as a function of word frequency.

		BITE BAR						**CHIN REST**					
		WORD FREQUENCY					**N**	**WORD FREQUENCY**					**N**
		1	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**	
		LOW				**HIGH**		**LOW**				**HIGH**	
FIRSTFD	MEAN	210	201	206	197	198	25	203	200	203	191	197	26
	SD	33	28.4	33.4	35.7	52.4	25	24.7	29.9	33	39	51.6	26
SECFD	MEAN	187	184	186	183	202	24	176	167	175	173	175	26
	SD	33.2	31	42.9	32.8	59.8	24	23.9	27.5	33.4	34.3	66.6	26
SFD	MEAN	238	216	219	219	218	31	224	208	211	212	206	31
	SD	43.8	35	32.9	34.3	41.7	31	30.1	24.1	25.5	28	25.6	31
$\text{TIME}_{\text{TOTAL}}$	MEAN	317	272	256	243	232	31	298	256	248	232	219	31
	SD	79.6	57.2	50.1	49.1	48.4	31	63.4	46.5	43.4	39.7	34	31
p_{SKIP}	MEAN	0.08	0.12	0.16	0.38	0.52	31	0.07	0.1	0.13	0.29	0.46	31
	SD	0.05	0.07	0.08	0.15	0.16	31	0.04	0.05	0.08	0.18	0.21	31
p_2	MEAN	0.2	0.17	0.11	0.06	0.04	31	0.18	0.15	0.11	0.06	0.04	31
	SD	0.07	0.09	0.07	0.05	0.04	31	0.07	0.07	0.06	0.04	0.03	31
p_{3+}	MEAN	0.05	0.03	0.01	0.01	0	31	0.05	0.03	0.01	0.01	0.01	31
	SD	0.05	0.03	0.01	0.01	0	31	0.04	0.03	0.01	0.01	0.01	31
p_{REGR}	MEAN	0.06	0.04	0.05	0.07	0.07	31	0.05	0.04	0.04	0.06	0.07	31
	SD	0.03	0.03	0.03	0.06	0.07	31	0.03	0.02	0.03	0.05	0.07	31

Table K2 Experiment 4 – reading with a bite bar (EXP) vs. chin rest reading data (CON). Means and standard deviations of four duration measures, and four probability measures as a function of word length.

			WORD LENGTH											
			2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**N**
FIRSTFD	**MEAN**	**EXP**	188	197	210	202	206	205	200	210	208	207	209	19
		CON	187	189	201	202	196	191	209	209	205	206	199	20
	SD	**EXP**	57.2	46.4	38.4	34.3	51.5	30	37.7	41.4	57.3	41.1	30.7	19
		CON	53.1	42.3	44.5	33.9	33.8	36.6	34.8	34.1	28.6	39.8	25.8	20
SECFD	**MEAN**	**EXP**	185	197	185	197	188	178	182	175	181	196	187	19
		CON	196	166	176	181	176	166	170	165	179	173	182	18
	SD	**EXP**	55.2	46.4	39.5	50.5	35.2	38.6	44.4	39.9	49.7	42.2	39.3	19
		CON	69.3	35.7	37.9	43.1	38.1	39.1	35.6	31.3	36.6	28.7	34.7	18
SFD	**MEAN**	**EXP**	219	219	222	228	216	217	230	242	235	235	229	26
		CON	218	210	210	216	206	206	226	230	223	231	220	30
	SD	**EXP**	39.3	34.2	39.3	37.5	34.6	36.4	46.4	49.8	56.2	44.1	47.3	26
		CON	28.5	27	24.3	27.8	25.5	28	29.6	40.4	51.4	51.4	34.9	30
TIME$_{\text{TOTAL}}$	**MEAN**	**EXP**	228	239	250	268	255	264	295	313	339	393	442	31
		CON	225	227	236	253	241	246	283	303	329	368	424	31
	SD	**EXP**	43.7	47	50.2	58.3	53.2	59.8	78.7	77.5	103.2	124.3	116	31
		CON	35.7	36.8	37	44.8	42.7	51.5	61.8	72.9	84.5	115.6	109.2	31
p_{SKIP}	**MEAN**	**EXP**	0.56	0.43	0.25	0.15	0.11	0.08	0.03	0.01	0.01	0.01	0	31
		CON	0.51	0.35	0.19	0.11	0.09	0.06	0.03	0.02	0	0.01	0	31
	SD	**EXP**	0.15	0.16	0.13	0.1	0.09	0.06	0.03	0.02	0.03	0.02	0.01	31
		CON	0.23	0.19	0.13	0.09	0.06	0.05	0.03	0.02	0.01	0.02	0.01	31
p_2	**MEAN**	**EXP**	0.02	0.05	0.08	0.11	0.12	0.15	0.2	0.26	0.32	0.34	0.43	31
		CON	0.02	0.05	0.07	0.1	0.11	0.13	0.2	0.25	0.3	0.33	0.36	31
	SD	**EXP**	0.03	0.04	0.06	0.07	0.08	0.1	0.1	0.14	0.16	0.17	0.15	31
		CON	0.03	0.04	0.05	0.06	0.07	0.09	0.1	0.13	0.16	0.13	0.12	31
p_3	**MEAN**	**EXP**	0	0	0.01	0.01	0.01	0.02	0.03	0.05	0.08	0.15	0.23	31
		CON	0	0	0	0.01	0.01	0.02	0.03	0.04	0.08	0.15	0.26	31
	SD	**EXP**	0.01	0.01	0.01	0.01	0.01	0.02	0.05	0.04	0.1	0.17	0.18	31
		CON	0.01	0.01	0.01	0.01	0.02	0.02	0.04	0.06	0.1	0.16	0.18	31
p_{REGR}	**MEAN**	**EXP**	0.07	0.07	0.07	0.06	0.04	0.05	0.05	0.03	0.03	0.03	0.03	31
		CON	0.09	0.06	0.05	0.05	0.04	0.03	0.03	0.03	0.02	0.03	0.03	31
	SD	**EXP**	0.09	0.06	0.04	0.04	0.04	0.03	0.04	0.03	0.06	0.05	0.04	31
		CON	0.08	0.05	0.03	0.04	0.03	0.03	0.03	0.03	0.04	0.05	0.04	31

Table K3 Experiment 4 – reading with a bite bar vs. chin rest reading data. Statistical analyses of four duration measures, and four probability measures. For each measure, an ANOVA with "experimental condition" (reading with a bite bar vs. reading with a chin rest) as between-subject factor and "word frequency" and/or "word length" as the respective within-subject factor was employed. * $p < .05$.

	Exp				**Word Frequency**				**Exp × Word Frequency**			
	MSE	**F (1,60)**	**p**	**η^2**	**MSE**	**F (4,57)**	**p**	**η^2**	**Ms**	**F (4,57)**	**p**	**η^2**
FirstFd	4157.299	1.140	.291	.023	851.277	3.215	**.033***	.062	418.809	.492	.653	.010
SecFd	4194.570	7.744	**.008***	.139	2208.399	1.095	.332	.022	398.599	.180	.804	.004
SFD	4674.369	1.507	.224	.025	324.756	22.362	**.000***	.272	267.604	.824	.447	.014
$\text{Time}_{\text{Total}}$	11863.316	1.210	.276	.020	1023.987	125.633	**.000***	.677	571.510	.558	.568	.009
P_{Skip}	.048	3.083	**.084**	.049	.023	265.809	**.000***	.816	.053	2.265	.130	.036
P_2	.014	.320	.573	.005	.003	183.947	**.000***	.754	.003	1.197	.305	.020
P_{3+}	.002	.016	.901	.000	.001	64.085	**.000***	.516	.000	.151	.786	.003
P_{Regr}	.006	.586	.447	.010	.003	10.001	**.000***	.143	.001	.289	.694	.005
	Exp				**Word Length**				**Exp × Word Length**			
	MSE	**F (1,60)**	**p**	**η^2**	**MSE**	**F (10,51)**	**p**	**η^2**	**MSE**	**F (10,51)**	**p**	**η^2**
FirstFd	6885.442	.381	.541	.011	1978.988	1.247	.293	.035	1505.028	.761	.558	.022
SecFd	6779.808	.022	.883	.001	1843.216	1.229	.297	.037	1347.967	.731	.607	.022
SFD	11830.576	.516	.476	.010	1053.346	9.352	**.000***	.152	721.882	.685	.620	.013
$\text{Time}_{\text{Total}}$	43436.023	.762	.386	.013	6872.488	164.283	**.000***	.732	2038.776	.297	.785	.005
P_{Skip}	.038	2.993	**.089**	.048	.036	293.820	**.000***	.830	.077	2.131	.128	.034
P_2	.047	.651	.423	.011	.019	135.269	**.000***	.693	.017	.881	.471	.014
P_{3+}	.024	.032	.858	.001	.028	72.946	**.000***	.549	.007	.248	.752	.004
P_{Regr}	.008	.693	.409	.011	.004	12.486	**.000***	.172	.004	.997	.405	.016

Appendix L

Tables Belonging to Chapter 2.5,
Global Analyses of Experiment 5, “Benchmark Plots”
– Word-Based Descriptive Statistics, Statistical Analyses –

Table L1 Experiment 5 – reading with low contrast vs. normal reading control data. Means and standard deviations of four duration measures, and four probability measures as a function of word frequency.

		Low Contrast						**Normal Reading**					
		Word Frequency					**N**	**Word Frequency**					**N**
		1 **Low**	**2**	**3**	**4**	**5** **High**		**1** **Low**	**2**	**3**	**4**	**5** **High**	
FirstFd	Mean	214	201	199	201	193	17	198	191	192	185	193	77
	Sd	33.3	29.9	31.5	39.2	58.8	17	30.3	30.8	35.8	31.2	55.3	77
SecFd	Mean	177	164	175	166	173	17	168	160	164	167	170	77
	Sd	28.9	27.4	31.8	34.4	65	17	27.7	30.7	33.2	39.9	108.1	77
SFd	Mean	234	213	214	214	208	26	210	195	199	201	199	107
	Sd	26.8	24.3	26.4	29.8	34.1	26	34.2	29.9	30.4	32.8	34.8	107
$\textbf{Time}_{\textbf{Total}}$	Mean	301	257	241	228	220	26	275	238	228	217	210	107
	Sd	56.9	42.1	35.1	34.8	40.1	26	62.8	46.4	41.2	39.8	41.3	107
$\boldsymbol{P}_{\textbf{Skip}}$	Mean	0.08	0.11	0.18	0.39	0.56	26	0.09	0.12	0.18	0.39	0.54	107
	Sd	0.06	0.09	0.11	0.14	0.11	26	0.05	0.07	0.1	0.17	0.16	107
$\boldsymbol{P}_{\textbf{2}}$	Mean	0.18	0.15	0.08	0.04	0.02	26	0.18	0.14	0.09	0.05	0.03	107
	Sd	0.07	0.08	0.05	0.03	0.03	26	0.08	0.07	0.06	0.04	0.04	107
$\boldsymbol{P}_{3+}$	Mean	0.04	0.02	0.01	0	0	26	0.04	0.02	0.01	0	0	107
	Sd	0.04	0.02	0.01	0.01	0	26	0.04	0.02	0.01	0.01	0.01	107
$\boldsymbol{P}_{\textbf{Regr}}$	Mean	0.06	0.05	0.05	0.07	0.07	26	0.05	0.04	0.05	0.06	0.07	107
	Sd	0.04	0.05	0.07	0.07	0.07	26	0.03	0.03	0.04	0.06	0.07	107

Table L2 Experiment 5 – reading with low contrast (Exp) vs. normal reading control data (Con). Means and standard deviations of four duration measures, and four probability measures as a function of word length.

			Word Length											
			2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**N**
FirstFd	**Mean**	**Exp**	180	189	207	209	198	209	208	204	216	214	213	11
		Con	185	192	193	197	192	193	198	193	198	200	195	53
	Sd	**Exp**	27.8	36.4	42.9	40.9	44.6	42	37.3	41.8	48.4	44.6	37.3	11
		Con	43.3	42.9	44.5	36	37.9	40	43.8	33.7	42.9	36.5	29.7	53
SecFd	**Mean**	**Exp**	206	174	165	169	175	168	178	164	189	190	175	10
		Con	167	166	162	170	164	159	162	161	166	170	166	52
	Sd	**Exp**	146.1	38.9	54.6	37.5	42.5	44.4	35	35.8	62.7	60.9	31	10
		Con	61.3	50.6	45	37.6	43.7	31.7	35.1	33.8	47.1	39.5	33.2	52
SFD	**Mean**	**Exp**	216	214	216	219	212	213	231	234	228	238	231	24
		Con	207	201	201	204	193	194	209	212	205	216	205	103
	Sd	**Exp**	36.2	31.6	30	28.1	25.2	24.2	27.8	27.2	34.4	33.1	29.3	24
		Con	40.1	32.7	29.9	31.1	30.5	31.3	36.5	35.6	36.7	41.8	40.3	103
Time$_{\text{Total}}$	**Mean**	**Exp**	217	228	238	250	239	247	282	292	326	350	423	26
		Con	211	215	221	238	222	229	259	273	293	319	379	107
	Sd	**Exp**	39.4	36.3	36.1	41.5	37.3	41.8	52.3	56.9	71.9	77.5	105.7	26
		Con	43.6	39.9	39.8	42.9	41.9	47.1	59.3	70	76.9	87.8	106.5	107
p_{Skip}	**Mean**	**Exp**	0.62	0.44	0.24	0.16	0.11	0.08	0.04	0.02	0.02	0.01	0.01	26
		Con	0.59	0.44	0.25	0.16	0.12	0.08	0.04	0.02	0.01	0	0	107
	Sd	**Exp**	0.12	0.14	0.14	0.12	0.11	0.08	0.04	0.03	0.04	0.02	0.01	26
		Con	0.17	0.16	0.14	0.11	0.09	0.06	0.04	0.02	0.04	0.01	0.01	107
p_2	**Mean**	**Exp**	0.01	0.03	0.06	0.09	0.09	0.12	0.16	0.23	0.35	0.38	0.38	26
		Con	0.02	0.04	0.06	0.09	0.1	0.12	0.18	0.24	0.31	0.34	0.4	107
	Sd	**Exp**	0.03	0.03	0.04	0.05	0.06	0.08	0.09	0.14	0.19	0.21	0.12	26
		Con	0.04	0.04	0.04	0.06	0.06	0.07	0.11	0.14	0.2	0.18	0.14	107
p_3	**Mean**	**Exp**	0	0	0	0.01	0.01	0.01	0.02	0.03	0.04	0.09	0.23	26
		Con	0	0	0	0.01	0.01	0.01	0.02	0.04	0.06	0.09	0.21	107
	Sd	**Exp**	0.01	0	0.01	0.01	0.02	0.02	0.03	0.04	0.06	0.09	0.19	26
		Con	0	0	0.01	0.01	0.01	0.01	0.03	0.04	0.09	0.11	0.17	107
p_{Regr}	**Mean**	**Exp**	0.08	0.08	0.06	0.06	0.05	0.04	0.04	0.04	0.03	0.04	0.05	26
		Con	0.07	0.07	0.06	0.06	0.04	0.04	0.04	0.03	0.02	0.04	0.03	107
	Sd	**Exp**	0.07	0.07	0.07	0.07	0.06	0.05	0.03	0.04	0.07	0.05	0.05	26
		Con	0.07	0.06	0.05	0.04	0.03	0.03	0.03	0.04	0.04	0.05	0.05	107

Table L3 Experiment 5 – reading with low contrast vs. normal reading control data. Statistical analyses of four duration measures, and four probability measures. For each measure, an ANOVA with "experimental condition" (reading with low contrast vs. normal reading) as between-subject factor and "word frequency" and/or "word length" as the respective within-subject factor was employed. * $p < .05$.

	Exp				**Word Frequency**				**Exp × Word Frequency**			
	MSE	**F (1,131)**	**p**	**η^2**	**MSE**	**F (4,128)**	**p**	**η^2**	**Ms**	**F (4,128)**	**p**	**η^2**
FirstFd	4537.000	1.471	.228	.016	1435.447	3.593	**.032***	.038	1341.603	.935	.390	.010
SecFd	6405.826	.122	.727	.001	6142.878	.668	.457	.007	1263.514	.206	.722	.002
SFD	4499.194	5.745	**.018***	.042	235.211	35.514	**.000***	.213	1038.780	4.416	**.009***	.033
$\text{Time}_{\text{Total}}$	9364.451	2.819	**.096**	.021	665.197	206.307	**.000***	.612	1971.953	2.964	**.053**	.022
P_{Skip}	.045	.003	.959	.000	.014	579.872	**.000***	.816	.007	.482	.583	.004
P_2	.012	.137	.712	.001	.003	258.892	**.000***	.664	.002	.638	.521	.005
P_{3+}	.001	.034	.855	.000	.001	85.723	**.000***	.396	9.909E-05	.127	.812	.001
P_{Regr}	.009	.206	.651	.002	.002	11.470	**.000***	.081	6.974E-05	.032	.964	.000

	Exp				**Word Length**				**Exp × Word Length**			
	MSE	**F (1,131)**	**p**	**η^2**	**MSE**	**F (10,122)**	**p**	**η^2**	**Ms**	**F (10,122)**	**p**	**η^2**
FirstFd	9959.522	.336	.564	.006	955.427	3.504	**.001***	.058	767.318	.803	.581	.014
SecFd	8762.170	.864	.357	.016	3212.688	1.990	.093	.036	4934.538	1.536	.189	.028
SFD	8070.394	7.389	**.008***	.056	766.506	14.885	**.000***	.107	1571.707	2.050	.079	.016
$\text{Time}_{\text{Total}}$	9959.522	.336	.564	.006	955.427	3.504	**.001***	.058	767.318	.803	.581	.014
P_{Skip}	.043	.001	.970	.000	.025	573.401	**.000***	.814	.010	.389	.709	.003
P_2	.057	.000	.997	.000	.023	186.229	**.000***	.587	.027	1.164	.325	.009
P_{3+}	.015	.020	.889	.000	.021	97.295	**.000***	.426	.010	.495	.584	.004
P_{Regr}	.013	.522	.471	.004	.003	15.069	**.000***	.103	.001	.398	.853	.003

Appendix M

Tables Belonging to Chapter 3.2,
Influence of Experimental Manipulations on Parameters of the OVP Function,
– Descriptive Statistics –

Table M1 Quadratic fit to refixation probability curves for *z* string "reading" data vs. "normal" reading control data: Estimates of parameters *A*, *B'*, *CC* and *C'*.

WORD LENGTH	CENTER OF WORD	MINDLESS READING					NORMAL READING				
		A	*B'*	*CC*	*C'*	χ^2	*A*	*B'*	*CC*	*C'*	χ^2
3	2	0.015	0.441	0.11	0.7	0	0.021	0.252	-0.5	0.5	0
4	2.5	0.011	0.672	0.52	0.76	0.0005	0.022	0.48	-0.33	0.54	0.0001
5	3	0.022	0.825	0.77	0.75	0.0011	0.013	0.8	0.09	0.62	0.0019
6	3.5	0.033	0.9	1.03	0.76	0.0031	0.024	0.756	0.23	0.62	0.0033
7	4	0.065	0.98	1.22	0.75	0.0075	0.036	0.98	0.36	0.62	0.0099
8	4.5	0.023	0.704	2.86	0.92	0.0094	0.077	1.152	0.67	0.65	0.0041

Note. χ^2 denotes sum of squared residuals.

Table M2 Quadratic fit to refixation probability curves for reading with salient OVP data vs. normal reading control data: Estimates of parameters *A*, *B'*, *CC* and *C'*.

WORD LENGTH	CENTER OF WORD	READING WITH SALIENT OVP					NORMAL READING				
		A	*B'*	*CC*	*C'*	χ^2	*A*	*B'*	*CC*	*C'*	χ^2
3	2	0.034	0.342	-0.55	0.48	0.0004	0.027	0.225	-0.54	0.49	0
4	2.5	0.031	0.528	-0.2	0.57	0.0009	0.017	0.464	-0.16	0.58	0.0003
5	3	0.027	0.85	0.04	0.61	0.0023	0.012	0.75	0.06	0.61	0.0022
6	3.5	0.026	0.828	0.55	0.67	0.01	0.013	0.792	0.35	0.64	0.0052
7	4	0.057	0.98	0.43	0.63	0.0013	0.015	0.931	0.55	0.65	0.0073
8	4.5	0.092	1.152	0.82	0.67	0.0047	0.051	1.152	0.5	0.63	0.0126

Note. χ^2 denotes sum of squared residuals.

Table M3 Quadratic fit to refixation probability curves for reading with a bite bar data vs. chin rest reading control data: Estimates of parameters *A*, *B'*, *CC* and *C'*.

WORD LENGTH	CENTER OF WORD	BITE BAR					CHIN REST				
		A	*B'*	*CC*	*C'*	χ^2	*A*	*B'*	*CC*	*C'*	χ^2
3	2	0.037	0.27	-0.21	0.6	0.0001	0.025	0.288	-0.35	0.55	0
4	2.5	0.034	0.448	0.07	0.64	0.0003	0.022	0.448	0.07	0.64	0.0006
5	3	0.032	0.725	0.21	0.64	0.0029	0.024	0.675	0.21	0.64	0.0028
6	3.5	0.036	0.9	0.22	0.62	0.0055	0.014	0.828	0.36	0.64	0.0044
7	4	0.055	0.98	0.33	0.62	0.004	0.041	0.931	0.35	0.62	0.0036
8	4.5	0.1	1.088	0.5	0.63	0.0054	0.096	1.216	0.5	0.63	0.0177

Note. χ^2 denotes sum of squared residuals.

Table M4 Quadratic fit to refixation probability curves for low contrast reading data vs. normal reading control data: Estimates of parameters *A*, *B'*, *CC* and *C'*.

WORD LENGTH	CENTER OF WORD	LOW CONTRAST READING					NORMAL READING				
		A	*B'*	*CC*	*C'*	χ^2	*A*	*B'*	*CC*	*C'*	χ^2
3	2	0.021	0.243	-0.57	0.48	0	0.027	0.225	-0.54	0.49	0
4	2.5	0.018	0.528	-0.26	0.56	0.0003	0.017	0.464	-0.16	0.58	0.0003
5	3	0.006	0.9	-0.02	0.6	0.0055	0.012	0.75	0.06	0.61	0.0022
6	3.5	0.02	0.792	0.21	0.62	0.0058	0.013	0.792	0.35	0.64	0.0052
7	4	0.038	1.127	0	0.57	0.0096	0.015	0.931	0.55	0.65	0.0073
8	4.5	0.065	1.088	0.5	0.63	0.0186	0.051	1.152	0.5	0.63	0.0126

Note. χ^2 denotes sum of squared residuals.

Appendix N

Tables Belonging to Chapter 4.4, Influence of Experimental Manipulations on Parameters of the PVL Curve,

– Descriptive Statistics –

Table N1 Normal fit to word-length dependent landing position distributions for *z* string “reading” data vs. “normal” reading control data: Estimates of parameters M, M_C, M' and SD.

WORD LENGTH	CENTER OF WORD	MINDLESS READING					NORMAL READING				
		M	M_C	M'	SD	χ^2	M	M_C	M'	SD	χ^2
3	2	2.18	0.18	0.73	2.14	0.00338	2.29	0.29	0.76	2.13	0.00469
4	2.5	2.54	0.04	0.64	2.48	0.00714	2.46	-0.04	0.62	2.41	0.00655
5	3	2.83	-0.17	0.57	2.67	0.00635	2.98	-0.02	0.6	2.41	0.00443
6	3.5	3.04	-0.46	0.51	2.64	0.00785	3.05	-0.45	0.51	2.7	0.00736
7	4	3.09	-0.91	0.44	2.71	0.00868	2.95	-1.05	0.42	2.48	0.00941
8	4.5	3.48	-1.02	0.43	3.14	0.0119	3.35	-1.15	0.42	2.7	0.01025

Note. $M_C = M$ – Center of word. $M' = M/$ word length. χ^2 denotes sum of squared residuals.

Table N2 Normal fit to word-length dependent landing position distributions for reading with salient OVP data vs. normal reading control data: Estimates of parameters M, M_C, M' and SD.

WORD LENGTH	CENTER OF WORD	READING WITH SALIENT OVP					NORMAL READING				
		M	M_C	M'	SD	χ^2	M	M_C	M'	SD	χ^2
3	2	2.35	0.35	0.78	2.1	0.00478	2.21	0.21	0.74	2.24	0.00505
4	2.5	2.61	0.11	0.65	2.42	0.00753	2.64	0.14	0.66	2.34	0.00644
5	3	2.79	-0.21	0.56	2.26	0.00545	2.95	-0.05	0.59	2.51	0.00614
6	3.5	2.91	-0.59	0.48	2.57	0.00652	3.21	-0.29	0.53	2.47	0.0078
7	4	3.2	-0.8	0.46	2.76	0.00877	3.27	-0.73	0.47	2.52	0.01069
8	4.5	3.47	-1.03	0.43	2.87	0.00975	3.4	-1.1	0.43	2.45	0.01231

Note. $M_C = M$ – Center of word. $M' = M/$ word length. χ^2 denotes sum of squared residuals.

Table N3 Normal fit to word-length dependent landing position distributions for reading with a bite bar data vs. chin rest reading control data: Estimates of parameters *M*, M_C, *M'* and *SD*.

Word length	Center of word	Bite Bar					Chin Rest				
		M	M_C	*M'*	*SD*	χ^2	*M*	M_C	*M'*	*SD*	χ^2
3	2	2.31	0.31	0.77	2.39	0.00568	2.13	0.13	0.71	1.94	0.0021
4	2.5	2.92	0.42	0.73	2.68	0.00908	2.54	0.04	0.64	2.12	0.00594
5	3	3.05	0.05	0.61	2.52	0.00683	2.71	-0.29	0.54	1.99	0.00472
6	3.5	3.34	-0.16	0.56	2.7	0.00703	2.9	-0.6	0.48	2	0.00876
7	4	3.28	-0.72	0.47	2.19	0.01083	2.74	-1.26	0.39	2	0.00788
8	4.5	3.61	-0.89	0.45	2.26	0.00982	3.26	-1.24	0.41	2.01	0.01054

Note. M_C = *M* – Center of word. *M'* = *M*/ word length. χ^2 denotes sum of squared residuals.

Table N4 Normal fit to word-length dependent landing position distributions for low contrast reading data vs. normal reading control data: Estimates of parameters *M*, M_C, *M'* and *SD*.

Word length	Center of word	Reading With Low Contrast					Normal Reading				
		M	M_C	*M'*	*SD*	χ^2	*M*	M_C	*M'*	*SD*	χ^2
3	2	2.08	0.08	0.69	2.18	0.00474	2.21	0.21	0.74	2.24	0.00505
4	2.5	2.68	0.18	0.67	2.48	0.00629	2.64	0.14	0.66	2.34	0.00644
5	3	3.03	0.03	0.61	2.18	0.00723	2.95	-0.05	0.59	2.51	0.00614
6	3.5	2.92	-0.58	0.49	2.06	0.00893	3.21	-0.29	0.53	2.47	0.0078
7	4	3.13	-0.87	0.45	2.02	0.00917	3.27	-0.73	0.47	2.52	0.01069
8	4.5	3.37	-1.13	0.42	2.07	0.01192	3.4	-1.1	0.43	2.45	0.01231

Note. M_C = *M* – Center of word. *M'* = *M*/ word length. χ^2 denotes sum of squared residuals.

Appendix O

Tables Belonging to Chapter 4.4,
Influence of Experimental Manipulations on Parameters of the PVL Curve,
– Statistical Analyses –

Table O1 ANOVA on mean (*M'*) and standard deviation (*SD*) of the PVL curve: Amount of variance explained by within-subject factors "experimental condition" (*z* string "reading" vs. normal reading) and "word length". * *p* < .05.

	Exp				**Word Length**				**Exp × Word Length**			
	Mse	**F (1,30)**	**p**	**η^2**	**Mse**	**F (5,26)**	**p**	**η^2**	**Mse**	**F (5,26)**	**p**	**η^2**
M'	.044	.006	.937	.000	.042	40.075	**.000***	.572	.020	.722	.553	.023
Sd	2.656	.875	.357	.028	1.429	4.541	**.004***	.131	.877	.845	.488	.027

Table O2 ANOVA on mean (*M'*) and standard deviation (*SD*) of the PVL curve: Amount of variance explained by between-subject factor "experimental condition" (reading with salient OVP vs. normal reading) and within-subject factor "word length". * *p* < .05.

	Exp				**Word Length**				**Exp × Word Length**			
	Mse	**F (1,141)**	**p**	**η^2**	**Mse**	**F (5,137)**	**p**	**η^2**	**Ms**	**F (5,137)**	**p**	**η^2**
M'	.085	.133	.716	.001	.042	74.254	**.000***	.345	.053	1.270	.285	.009
Sd	4.791	.177	.675	.001	.796	5.587	**.000***	.038	1.929	2.424	**.045***	.017

Table O3 ANOVA on mean (*M'*) and standard deviation (*SD*) of the PVL curve: Amount of variance explained by between-subject factor "experimental condition" (reading with a bite bar vs. reading with a chin rest) and within-subject factor "word length". * *p* < .05.

	Exp				**Word Length**				**Exp × Word Length**			
	Mse	**F (1,60)**	**p**	**η^2**	**Mse**	**F (5,56)**	**p**	**η^2**	**Ms**	**F (5,56)**	**p**	**η^2**
M'	.089	5.011	**.029***	.077	.033	55.403	**.000***	.480	.008	.236	.859	.004
Sd	3.024	6.198	**.016***	.094	.580	1.975	.097	.032	.711	1.226	.300	.020

Table O4 ANOVA on mean (*M'*) and standard deviation (*SD*) of the PVL curve: Amount of variance explained by between-subject factor "experimental condition" (reading with low contrast vs. normal reading) and within-subject factor "word length". * *p* < .05.

	Exp				**Word Length**				**Exp × Word Length**			
	Mse	**F (1,131)**	**p**	**η^2**	**Mse**	**F (5,127)**	**p**	**η^2**	**Ms**	**F (5,127)**	**p**	**η^2**
M'	.076	.390	.533	.003	.051	45.072	**.000***	.256	.032	.622	.572	.005
Sd	4.047	2.086	.151	.016	.678	.687	.615	.005	1.414	2.087	.074	.016

Appendix P

Tables Belonging to Chapter 5.2, Influence of Experimental Manipulations on Parameters of the IOVP Function, – Descriptive Statistics –

Table P1 Quadratic fit of Fixation-Duration IOVP curves for *z* string "reading" data vs. "normal" reading control data: Estimates of parameters *A*, *B'*, *CC* and *C'*.

WORD LENGTH	CENTER OF WORD	MINDLESS READING					NORMAL READING				
		A	*B'*	*CC*	*C'*	χ^2	*A*	*B'*	*CC*	*C'*	χ^2
3	2	255	-109	-0.52	0.49	504.25	206	-50	-0.34	0.55	220.57
4	2.5	268	-188	-0.65	0.46	1748.76	212	-81	-0.96	0.39	950.46
5	3	265	-226	-0.51	0.5	1849.96	223	-125	-0.9	0.42	1540.46
6	3.5	274	-288	-0.81	0.45	4748.11	213	-127	-0.95	0.43	2128.17
7	4	277	-276	-0.93	0.44	6519.26	216	-145	-1.63	0.34	3846.29
8	4.5	286	-348	-1.07	0.43	17546.75	233	-244	-1.13	0.42	8316.05

Note. χ^2 denotes sum of squared residuals.

Table P2 Quadratic fit of Fixation-Duration IOVP curves for reading with salient OVP data vs. normal reading control data: Estimates of parameters *A*, *B'*, *CC* and *C'*.

WORD LENGTH	CENTER OF WORD	READING WITH SALIENT OVP					NORMAL READING				
		A	*B'*	*CC*	*C'*	χ^2	*A*	*B'*	*CC*	*C'*	χ^2
3	2	214	-57	-0.53	0.49	257.91	202	-50	-0.38	0.54	310.8
4	2.5	224	-119	-0.68	0.45	736.95	208	-85	-0.61	0.47	786.57
5	3	229	-132	-1.16	0.37	1486.6	217	-115	-1.02	0.4	1353.36
6	3.5	224	-174	-0.84	0.44	2496.71	212	-124	-1.17	0.39	2929.38
7	4	230	-210	-1.08	0.42	5100.73	215	-148	-1.26	0.39	4355.09
8	4.5	236	-277	-0.76	0.47	5356.58	229	-227	-1.2	0.41	8068.61

Note. χ^2 denotes sum of squared residuals.

Table P3 Quadratic fit of Fixation-Duration IOVP curves for reading with a bite bar data vs. chin rest reading control data: Estimates of parameters *A*, *B'*, *CC* and *C'*.

WORD LENGTH	CENTER OF WORD	BITE BAR					CHIN REST				
		A	*B'*	*CC*	*C'*	χ^2	*A*	*B'*	*CC*	*C'*	χ^2
3	2	216	-49	-0.27	0.58	218.26	209	-52	-0.5	0.5	172.18
4	2.5	230	-106	-0.53	0.49	1292.81	217	-87	-1.02	0.37	863.08
5	3	240	-148	-0.46	0.51	2752.36	231	-159	-1.1	0.38	1798.88
6	3.5	236	-166	-1.2	0.38	3609.72	226	-164	-0.74	0.46	3267.78
7	4	230	-167	-1.38	0.37	3470.06	225	-159	-1.25	0.39	5747.64
8	4.5	255	-245	-0.7	0.48	14191.17	245	-241	-0.78	0.47	12992.63

Note. χ^2 denotes sum of squared residuals.

Table P4 Quadratic fit of Fixation-Duration IOVP curves for low contrast reading data vs. normal reading control data: Estimates of parameters *A*, *B'*, *CC* and *C'*.

WORD LENGTH	CENTER OF WORD	LOW CONTRAST					NORMAL READING				
		A	*B'*	*CC*	*C'*	χ^2	*A*	*B'*	*CC*	*C'*	χ^2
3	2	214	-43	-0.27	0.58	310.4	202	-50	-0.38	0.54	310.8
4	2.5	225	-81	-0.69	0.45	932.23	208	-85	-0.61	0.47	786.57
5	3	229	-148	-1.15	0.37	1146.16	217	-115	-1.02	0.4	1353.36
6	3.5	234	-158	-0.97	0.42	3715.43	212	-124	-1.17	0.39	2929.38
7	4	244	-186	-1.5	0.36	8154.34	215	-148	-1.26	0.39	4355.09
8	4.5	253	-218	-1.48	0.38	14495.26	229	-227	-1.2	0.41	8068.61

Note. χ^2 denotes sum of squared residuals.

Appendix Q

Tables Belonging to Chapter 5.2,
Influence of Experimental Manipulations on Parameters of the IOVP Function,
– Statistical Analyses –

Table Q1 ANOVAs on parameters *A*, *B'*, and *C'* of the IOVP function: Amount of variance explained by within-subject factors "experimental condition" (*z* string "reading" vs. normal reading) and "word length". * *p* < .05.

	Exp				**Word Length**				**Exp × Word Length**			
	MSE	**F (1,30)**	**p**	η^2	**MSE**	**F (5,26)**	**p**	η^2	**MSE**	**F (5,26)**	**p**	η^2
A	7265.596	36.695	**.000***	.550	543.163	15.245	**.000***	.337	443.638	2.408	.055	.074
B'	45558.576	24.792	**.000***	.452	15718.150	27.355	**.000***	.477	14742.818	1.685	.165	.053
C'	.077	1.687	.204	.053	.063	2.443	**.047***	.075	.072	.886	.482	.029

Table Q2 ANOVAs on parameters *A*, *B'*, and *C'* of the IOVP function: Amount of variance explained by between-subject factor "experimental condition" (reading with salient OVP vs. normal reading) and within-subject factor "word length". * *p* < .05.

	Exp				**Word Length**				**Exp × Word Length**			
	MSE	**F (1,141)**	**p**	η^2	**MSE**	**F (5,137)**	**p**	η^2	**MS**	**F (5,137)**	**p**	η^2
A	5917.524	4.116	**.044***	.028	288.265	27.992	**.000***	.166	264.623	.918	.461	.006
B'	22416.475	9.699	**.002***	.064	9312.684	72.574	**.000***	.340	16513.786	1.773	.138	.012
C'	.115	.069	.794	.000	.078	3.517	**.006***	.024	.062	.787	.545	.006

Table Q3 ANOVAs on parameters *A*, *B'*, and *C'* of the IOVP function: Amount of variance explained by between-subject factor "experimental condition" (reading with a bite bar vs. reading with a chin rest) and within-subject factor "word length". * *p* < .05.

	Exp				**Word Length**				**Exp × Word Length**			
	MSE	**F (1,60)**	**p**	η^2	**MSE**	**F (5,56)**	**p**	η^2	**MS**	**F (5,56)**	**p**	η^2
A	6030.877	1.270	.264	.021	511.836	25.413	**.000***	.298	171.892	.336	.842	.006
B'	29928.681	.032	.858	.001	10671.303	33.862	**.000***	.361	2072.802	.194	.932	.003
C'	.141	1.074	.304	.018	.095	2.185	.070	.035	.129	1.348	.252	.022

Table Q4 ANOVAs on parameters *A*, *B'*, and *C'* of the IOVP function: Amount of variance explained by between-subject factor "experimental condition" (reading with low contrast vs. normal reading) and within-subject factor "word length". * *p* < .05.

	EXP				**WORD LENGTH**				**EXP × WORD LENGTH**			
	MSE	**F (1,131)**	**p**	η^2	**MSE**	**F (5,127)**	**p**	η^2	**MS**	**F (5,127)**	**p**	η^2
A	6211.830	7.409	**.007***	.054	347.115	36.098	**.000***	.216	1124.808	3.240	**.010***	.024
B'	23643.033	1.090	.298	.008	8628.345	47.071	**.000***	.264	14057.992	1.629	.166	.012
C'	.120	.067	.797	.001	.085	5.394	**.000***	.040	.026	.306	.892	.002