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Mislocated fixations during reading and the inverted optimal viewing position effect

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Abstract

Refixation probability during reading is lowest near the word center, suggestive of an optimal viewing position (OVP). Counter-intuitively, fixation durations are largest at the OVP, a result called the inverted optimal viewing position (IOVP) effect [Vitu, McConkie, Kerr, & O'Regan, (2001). Vision Research 41, 3513–3533]. Current models of eye-movement control in reading fail to reproduce the IOVP effect. We propose a simple mechanism for generating this effect based on error-correction of mislocated fixations due to saccadic errors. First, we propose an algorithm for estimating proportions of mislocated fixations from experimental data yielding a higher probability for mislocated fixations near word boundaries. Second, we assume that mislocated fixations trigger an immediate start of a new saccade program causing a decrease of associated durations. Thus, the IOVP effect could emerge as a result of a coupling between cognitive and oculomotor processes.
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1. Introduction

Fixation durations in reading are sensitive to local processing difficulty, as reflected in effects of word frequency and predictability (i.e., the probability to guess the word from the previous words of the sentence). This well-established link between cognitive processes of word recognition and eye-movement control (e.g., Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner, 1998) has been implemented in computational models of eye-movement control during reading (see Reichle, Rayner, & Pollatsek, 2003, for a recent review; Engbert, Longtin, & Kliegl, 2002). However, fixation durations are also influenced by low-level nonlinguistic factors like word length. Likewise, fixation durations systematically vary with within-word fixation position (Vitu, McCon-

kie, Kerr, & O'Regan, 2001). It is commonly accepted that within-word landing positions are the result of oculomotor errors (McConkie, Kerr, Reddix, & Zola, 1988). Thus, decisions about where to fixate next, as reflected in landing position distributions, have been largely attributed to the oculomotor plant rather than the cognitive control system of eye movements. The question how oculomotor errors affect fixation durations, however, has so far been neglected in theoretical models.

The word center is typically defined as the optimal viewing position (OVP), operationally defined as the position with a minimum refixation probability (cf., McConkie, Kerr, Reddix, Zola, & Jacobs, 1989, for continuous reading; O'Regan & Lévy-Schoen, 1987, for isolated words). As a consequence, fixation durations were expected to exhibit also a minimum at or near word centers. For gaze durations (i.e., the sum of all fixations on a word, excluding any fixations after the eyes have left the word), such an OVP effect was observed in an isolated word recognition paradigm (O'Regan,

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Lévy-Schoen, Pynte, & Brugaillère, 1984), but not in continuous reading (Vitu, O'Regan, & Mittau, 1990). For continuous reading, however, Vitu et al. (2001, see also O'Regan, Vitu, Radach, & Kerr, 1994) reported several inverted optimal viewing position (IOVP) effects for fixation durations: For example, single fixations (i.e., fixations on words that are fixated exactly once) were longest, not shortest, near the word centers. As an explanation for this counterintuitive effect, we propose that oculomotor errors often lead to mislocated fixations on unintended words. These errors are more likely to result in fixations at boundaries than centers of words. Assuming also that mislocated fixations immediately induce the start of error-correcting saccade programs, we predict that average fixation durations at word boundaries are shorter than at the optimal viewing position. We tested this theoretical explanation with a series of computational analyses; it is also compatible with several mathematical models.

1.1. Cognitive models vs. oculomotor models

Theoretical models of eye-movement control during reading can be classified into two general categories (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 et al., 2002; Reichle et al., 2003). 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 et al., 2003; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999). An SAS model with fewer internal states based on advanced stochastic methods was proposed as an alternative (Engbert & Kliegl, 2001; Engbert & Kliegl, 2003). 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 model (Engbert et al., 2002; Engbert, Kliegl, & Longtin, 2004; Kliegl & Engbert, 2003) is such a GAG variant that assumes spatially distributed lexical processing. In both theoretical frameworks, eye movements are driven by word recognition. 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.

The most prominent example of an oculomotor model is O'Regan's strategy-tactics model (1990, 1992; O'Regan & Lévy-Schoen, 1987). In addition, there have been proposals by McConkie et al. (1988), and McConkie et al. (1989). A more recent primary oculomotor model was suggested by Yang and 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.

In principle, the mechanism we propose 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., 2002) 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.

1.2. The optimal viewing position

The optimal fixation position for processing a word was originally derived from word identification curves in the isolated word presentation paradigm: The optimal viewing position 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, 1991; Vitu et al., 1990) 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., 2003, 1999; but see Vitu, 2003, proposing that the eyes move forward with no specific saccade target).

The current paper is strongly motivated by and related to extensive and seminal studies by McConkie et al. (1988) and Vitu et al. (2001). 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) = 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 goal of our study was to propose and test a new explanation for the fixation duration IOVP effect.

1.3. The IOVP effect as a consequence of correcting mislocated fixations

There is much variance associated with distributions of initial landing positions. Nevertheless, readers tend to make their first fixation about halfway between the beginning and the middle of the word (McConkie et al., 1988; Rayner, 1979; Vitu, 1991; Vitu et al., 2001). In an influential paper, McConkie et al. (1988) showed that this *preferred viewing location* (PVL)[1] 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). Thus, a given fixation location defines not only the landing site in a word, but it also defines the takeoff point or launch site for the next target word.

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

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[1] In contrast to the optimal viewing position (see Section 1.2), the preferred viewing location (Rayner, 1979) reflects where readers actually do land in a word. The PVL is a bit to the left of the OVP (O'Regan & Lévy-Schoen, 1987).

low-level oculomotor processes and is called the *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.

McConkie et al. (1988) computed that the mean of the landing position distribution is accurate (i.e., it equals the center of the target word), when the launch site is between six and seven letters to the left of the center of the target. Thus, for English readers the optimal center-based launch site distance appears to be six to seven letters. For saccades coming from this region, undershoots and overshoots are balanced. 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 (McConkie et al., 1988). An additional random error component, characterized by the standard deviation of the landing site distribution, increases with the distance of the launch site from the target word.

Our theory of mechanisms underlying the IOVP effect expands on the consequences of saccadic errors. 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). We provide an algorithm for estimating the proportion of these *mislocated fixations* from empirical data and suggest that IOVP effects are a consequence of mislocated fixations.

2. Experiment

2.1. Method

2.1.1. Participants

Data of young ($N = 33$; $M = 22$, range: 19–28 years) and older adults ($N = 32$; $M = 70$, range: 65–83 years) reported in Kliegl et al. (2004) were supplemented with participants varying in age between 16 and 80 years ($N = 115$; $M = 33$ years). In addition, a group of older adults who had been exposed to the sentences three to six month earlier was included ($N = 20$; $M = 74$, range: 66–79 years). Participants received study credit or were paid 5 €.

2.1.2. Apparatus, materials and procedure

Following 10 warm-up sentences, participants read 144 sentences of the Potsdam corpus comprising 1138 words. Excluding the first word of each sentence which was not used in the analyses, frequencies of word lengths

3–8 were: 222, 134, 147, 129, 92, 72. CELEX frequency norms (Baayen, Piepenbrock, & van Rijn, 1993) are available for all 1138 words. Each sentence contained a target word selected from the CELEX database contributing to a $2 \times 2 \times 3$ design with word class (noun vs. verb), printed frequency (high: >50 occurrences/million vs. low: 1–4 occurrences/million), and word length (short: 3 or 4 letters, medium: 5–7 letters, long: 8 or 9 letters) as factors. Three samples were tested with SR Research EyeLink I (250 Hz) and two samples with EyeLink II (500 Hz) systems. The EyeLink system measures a participant's gaze position with an average error of less than $0.5°$ of visual angle. Thus, calibrated gaze position was recorded accurately at the level of letters. Further details of materials, experimental procedure, and data selection are described in Kliegl et al. (2004).

2.2. Results

2.2.1. OVP and IOVP effects

To investigate the optimal viewing position in our data, we computed the fraction of initial fixations at different letter positions on words of lengths 3–8 that were immediately followed by a refixation on the word, that is we computed the refixation probability as a function of initial landing position for different word lengths (Fig. 1). Data were collapsed across all participants and all words of a given length. The curves are relatively smooth due to the large sample size ($N = 200$) and the considerable number of words (a corpus of 944 words).
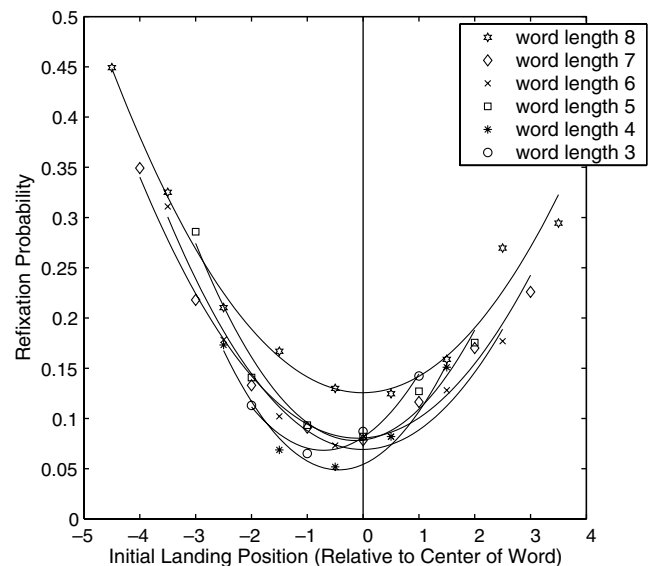

Fig. 1. Mean refixation probability as a function of the initial landing position within a word, for 3–8-letter words. The initial landing position in the word is plotted as letter position relative to the center of the word. For words of a given length, the leftmost position corresponds to the space to the left of the word.

Table 1
Quadratic fit to refixation curves: estimates for parameters *A*, *B* and *C*

Word length	Center of word	Parameters				Sum of squared residuals	Total *N*	Number of refixations
		A	*B*	*C*	C_R			
3	2	0.068	0.026	1.29	−0.71	0.0001	19,518	2004
4	2.5	0.049	0.028	2.06	−0.44	0.0003	14,569	1429
5	3	0.078	0.024	2.86	−0.14	0.001	16,989	2339
6	3.5	0.069	0.019	3.49	−0.01	0.0007	15,061	2018
7	4	0.08	0.017	3.91	−0.09	0.001	13,512	2055
8	4.5	0.126	0.016	4.49	−0.01	0.003	10,156	2192

Note: C_R = C—Center of word.

They show a clear minimum very close to word centers with a small leftward shift.

Following McConkie et al. (1989), the refixation curves depicted in Fig. 1 were fitted to a quadratic polynomial, i.e.

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

where *x* denotes the initial fixation position and *y* is the refixation probability. In Eq. (1), *C* indicates the OVP, whereas *A* indicates the minimum of the refixation probability at the 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. Numerical values for the three free parameters in Eq. (1) as well as for C_R as the center-based *C* value are given in Table 1. For German words of lengths 3–8, the OVP was at the center or up to 2/3 character positions to the left of the center of the word. Interestingly, for English data McConkie et al. (1989) found the OVP to be 1/4–1/2 character position to the right of the center of the word. Since the deviations from word center were very small, we conclude that the center of the word is the optimal viewing position.

Next, we investigated the effect of the initial landing position on mean durations for single and first fixations. To avoid redundancy, first-fixation duration was defined as the duration of the first of multiple fixations on a word in first pass reading, thus excluding single fixations.[2] Single fixation and first-fixation durations shorter than 30 ms or longer than 1 s were excluded from analyses. We replicated Vitu et al.'s (2001) inverted-OVP effect for both single (Fig. 2(a)) and first fixations (Fig.

2(b)), reflected in the inverted U-shapes of fixation durations as a function of the initial landing position within a word. For both single and first fixations and 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. It appears that the IOVP effect was considerably stronger for first fixations as compared to single fixations.

To estimate the IOVP effect quantitatively, we approximated the effect with the same quadratic polynomial as in Eq. (1), 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 2. For both single- and first-fixation durations and over 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 1), 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.

For each participant, an IOVP curve was estimated for single-fixation as well as first-fixation durations. Parameter *B* differed significantly from 0 [single-fixation duration: $t(199) > 14.3$, $p < 0.001$ for each word length; first-fixation duration: $t(199) > 18.5$, $p < 0.001$], corroborating the quadratic trend of fixation durations across landing positions. In addition, we examined the influence of word length on the parameters of the quadratic function (see Fig. 2). Note that word length itself is a confounding factor for the shape of the IOVP curves presented in Fig. 2. 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, 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

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[2] Note that first-fixation duration is traditionally defined as the duration of the first fixation on a word regardless of whether it is the only fixation on a word or the first of multiple fixations on a word (Rayner, 1998). Consequently, more than 85% of so-defined first fixations would be single fixations (computed from *N*'s in Table 2) resulting into a considerably overlap between data presented in Fig. 2(a) and (b). Therefore, we opted for a non-overlapping definition of first fixation.
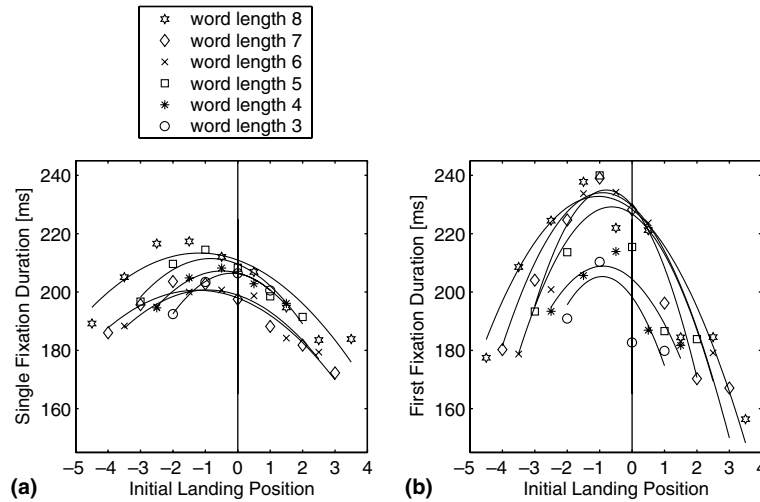
Fig. 2. Mean fixation duration as a function of word length and initial landing position within a word, for single (a) and first (b) fixations and 3–8-letter words.

Table 2
Quadratic fit of IOVP curves for single and first-fixation durations: estimates of parameters *A*, *B* and *C*

Word length	Center of word	Single fixation durations								First-fixation durations							
		A	*B*	*B′*	*C*	C_R	*C′*	χ^2	*N*	*A*	*B*	*B′*	*C*	C_R	*C′*	χ^2	*N*
3	2	206	−4.2	−38	1.82	−0.18	0.61	0.04	17,981	205	−8.3	−75	1.08	−0.92	0.36	316.9	1483
4	2.5	207	−3	−48	2.02	−0.48	0.51	4.33	13,157	209	−5.5	−88	1.6	−0.9	0.4	183.9	1375
5	3	211	−2.8	−70	2.17	−0.83	0.43	35.93	14,818	235	−8.2	−205	2.2	−0.8	0.44	974.9	2126
6	3.5	201	−2	−72	2.56	−0.94	0.43	33	12,922	229	−6.1	−220	2.87	−0.63	0.48	602.1	2093
7	4	201	−1.7	−83	2.75	−1.25	0.39	45.12	11,158	234	−5.5	−270	3.09	−0.91	0.44	977.7	2312
8	4.5	213	−1.7	−109	3.31	−1.19	0.41	236.91	7851	233	−4.1	−262	3.46	−1.04	0.43	723.4	2269

Note: $C_R = C$—Center of word. χ^2 denotes sum of squared residuals.

parameters *B* and *C* to $B′ = B \cdot L^2$ and $C′ = C/L$. The transformed values for *B′* and *C′* are listed in Table 2. 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 IOVP effect for single and first-fixation durations. We used these parameters as dependent variables in analyses of variance (ANOVA) with word length as within-subject factor. Word length was significant in all analyses (all $Fs > 24$, $p < 0.001$, $\eta^2 \geqslant 0.108$ for ANOVAs on *A* and *B′*, and $Fs > 3$, $p < 0.05$, $\eta^2 \leqslant 0.047$ for ANOVAs on *C′*). Moreover, both linear (all $Fs > 38$, $p < 0.001$, $\eta^2 \geqslant 0.161$) and quadratic trends (all $Fs > 4.8$, $p < 0.05$, $\eta^2 \geqslant 0.024$) were consistently significant, except for *C′* in the analysis of first-fixation durations where the linear trend was not significant.

Finally, we investigated the effect of initial fixation position on gaze durations (i.e., the sum of initial fixation and all refixations on a word before the eyes move on to another word, see Fig. 3). Roughly,
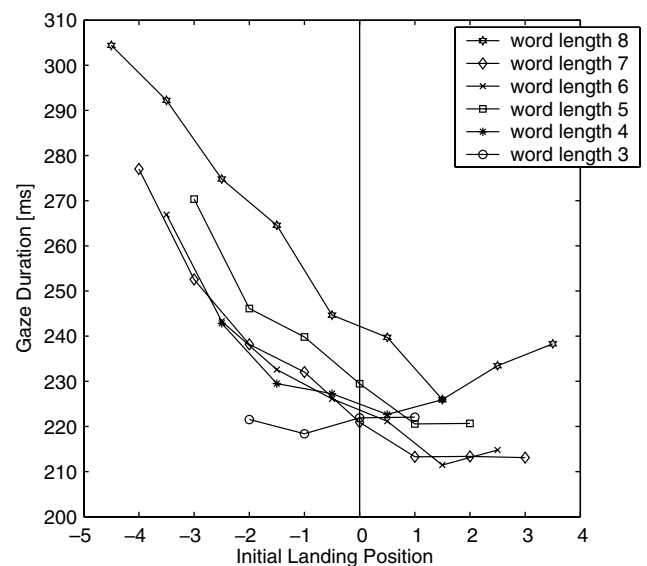

Fig. 3. Mean gaze duration as a function of the initial landing position within a word, for 3–8-letter words.

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. 1). In addition, durations of fixations at the end of words were somewhat shorter than those at the beginning (see Fig. 2). Therefore, we observed rudimentary U-shaped curves for gaze durations with a decreasing trend across fixation positions (see Fig. 3).

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 (20–40 ms). Table 3 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 180–250 ms (Becker & Jürgens, 1979). Even if uncertainty about when or where to move the eyes was eliminated, saccade latency was at least 150–175 ms (Rayner, Slowiaczek, Clifton, & Bertera, 1983). We suspected that the latency for refixation saccades would have to be placed at the lower end of this range and therefore set the time needed to program a refixation saccade to $\tau_R = 150$ ms. Furthermore, for simplicity we 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 1 yield an increase of gaze duration of 35 ms [$=150(0.08 + 0.017(1 - 4)^2)$]. Conversely, the single-fixation duration "benefit" for not fixating the center of word only amounts to 15 ms [$=1.7(1 - 4)^2$ with B_7 from Table 2]. 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.

2.2.2. Analysis of variables interacting with IOVP

Guided initially by Vitu et al.'s (2001) analyses, we carried out various post-hoc analyses to determine variables that interact with the IOVP effect. Given the large number of participants, a 1%-error level was adopted for statistical significance. Most importantly, we replicated and extended a frequency effect on fixation durations that was independent of landing position (Rayner et al., 1996; Vitu et al., 2001). Fig. 4 displays results for corpus target words [i.e., one word per sentence constituting an orthogonal word length (3) × word frequency (2) design with 24 words in each cell]. Depicted are 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: 1–4 occurrences/million) as a function of the landing zone initially fixated. Words of all lengths were divided into five zones (cf., Vitu et al., 2001), and data for each zone were averaged across word lengths and subjects. A fixation duration IOVP effect was found for every word length × word frequency combination (Fig. 4).

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. First, single-fixation durations increased with length [$F(1,2) = 11.815$, MSE = 1990.255, $p = .000$, $\eta^2 = .056$]

Table 3
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)	25.8	14.1	10.2	14.1	0	0	0	0	0
	Duration gain G (ms)	16.8	4.2	0	4.2	0	0	0	0	0
4	Refixation cost R (ms)	33.6	16.8	8.4	8.4	16.8	0	0	0	0
	Duration gain G (ms)	18.8	6.8	0.8	0.8	6.8	0	0	0	0
5	Refixation cost R (ms)	44.1	26.1	15.3	11.7	15.3	26.1	0	0	0
	Duration gain G (ms)	25.2	11.2	2.8	0	2.8	11.2	0	0	0
6	Refixation cost R (ms)	45.3	28.2	16.8	11.1	11.1	16.8	28.2	0	0
	Duration gain G (ms)	24.5	12.5	4.5	0.5	0.5	4.5	12.5	0	0
7	Refixation cost R (ms)	52.8	35	22.2	14.6	12	14.6	22.2	35	0
	Duration gain G (ms)	27.2	15.3	6.8	1.7	0	1.7	6.8	15.3	0
8	Refixation cost R (ms)	67.4	48.2	33.8	24.2	19.4	19.4	24.2	33.8	48.2
	Duration gain G (ms)	34.4	20.8	10.6	3.8	0.4	0.4	3.8	10.6	20.8
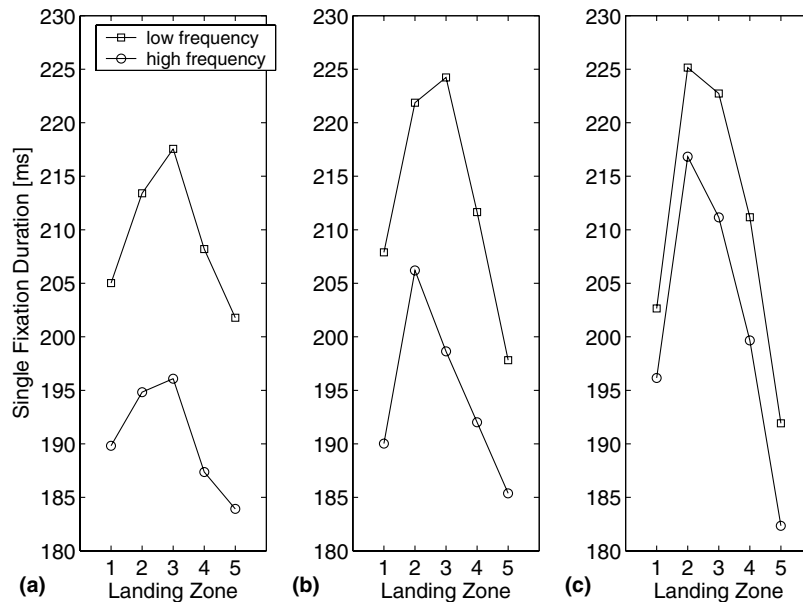
Fig. 4. Mean duration of single fixations on target words of different lengths (a: 3 and 4, b: 5–7, c: 8 and 9) and frequency (high vs. low) as a function of the landing zone initially fixated. Words of all lengths were divided into five zones, and data for each zone were averaged across word lengths and subjects.

and decreased with frequency [$F(1,1) = 151.072$, $MSE = 2078.383$, $p = .000$, $\eta^2 = .432$], see also Kliegl et al. (2004). The frequency effect decreased for longer words [$F(1,2) = 6.604$, MSE = 1799.467, $p = .002$, $\eta^2 = .032$ 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 [$F(1,2) = 8.767$, MSE = 859.923, $p = .000$, $\eta^2 = .042$]. Importantly for the current paper, there was a significant main effect for landing zone [$F(1,4) = 32.573$, MSE = 2519.912, $p = .000$, $\eta^2 = .141$] reflecting the IOVP effect and a significant interaction of word length and landing zone [$F(1,8) = 6.564$, MSE = 1902.686, $p = .000$, $\eta^2 = .032$] with a stronger landing zone effect (=IOVP effect) for longer words. Finally, the interaction between word frequency and landing zone was not significant [$F(1,4) = 2.196$, MSE = 1582.237, $p = .068$, $\eta^2 = .011$]. Thus, single fixations on low frequency words were consistently longer than on high frequency words with this effect being independent of landing zone (Rayner et al., 1996; Vitu et al., 2001).

3. The IOVP effect as the result of error-correction of mislocated fixations

The analysis to check the hypothesis that saccade-error-correction underlies the IOVP effect was performed in three steps. First, we estimated the parameters of normal distributions for landing positions (Section 3.1). Second, we calculated the probability for mis-located fixations as a function of landing position based on the overlap of landing position distributions to neighboring words (Section 3.2). Third, we tested the assumption that an error-correction of mislocated fixations reproduces the IOVP quantitatively (Section 3.3).

3.1. 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; Rayner, 1979). Potentially, all types of fixations (i.e., not only initial fixations) can contribute to mislocated fixations. Therefore, we computed landing position distributions for all fixations except the first and last fixations in a sentence (Fig. 5). 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.[3] In comparison with the optimal viewing position (Fig. 1), the preferred viewing position was slightly shifted to the left (O'Regan & Lévy-Schoen, 1987).

The relatively broad composite distributions displayed in Fig. 5 can be decomposed by splitting the data

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[3] Initial fixations which correspond to first fixations (traditional definition, see Footnote 2) make up about 70% of all fixations.
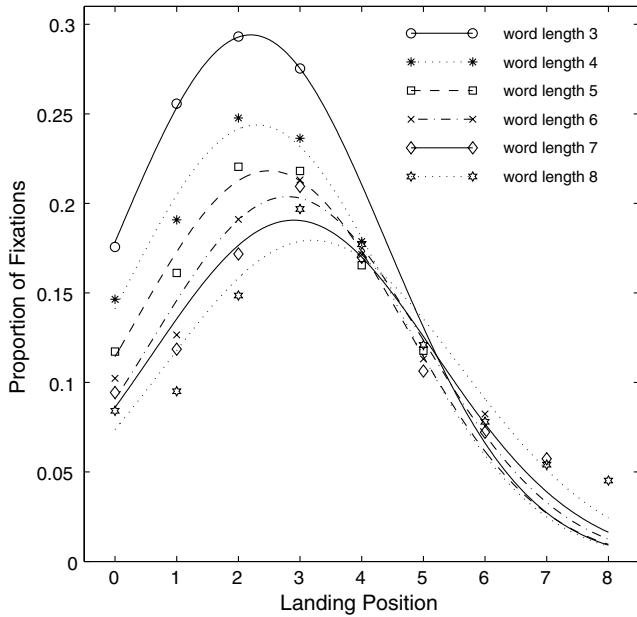
Fig. 5. Landing position distributions for 3–8-letter words. Letter 0 corresponds to the space to the left of the word. Also presented is the best-fitting normal curve for each distribution.

by launch site distance (Fig. 6). Note that only initial fixations were considered to facilitate a direct compari-

son with the widely-cited English data by McConkie et al. (1988) whose analyses were based on a sample of 66 college students. Table 4 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.

The landing-site distributions were in good agreement with those reported by McConkie et al. (1988): (1) Landing sites 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. 6). Specifically, for every 1-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: 0.41–0.53). In addition, we computed 5.4 letters as the average optimal distance between launch site and the center of the target word (range: 4.8–5.6).
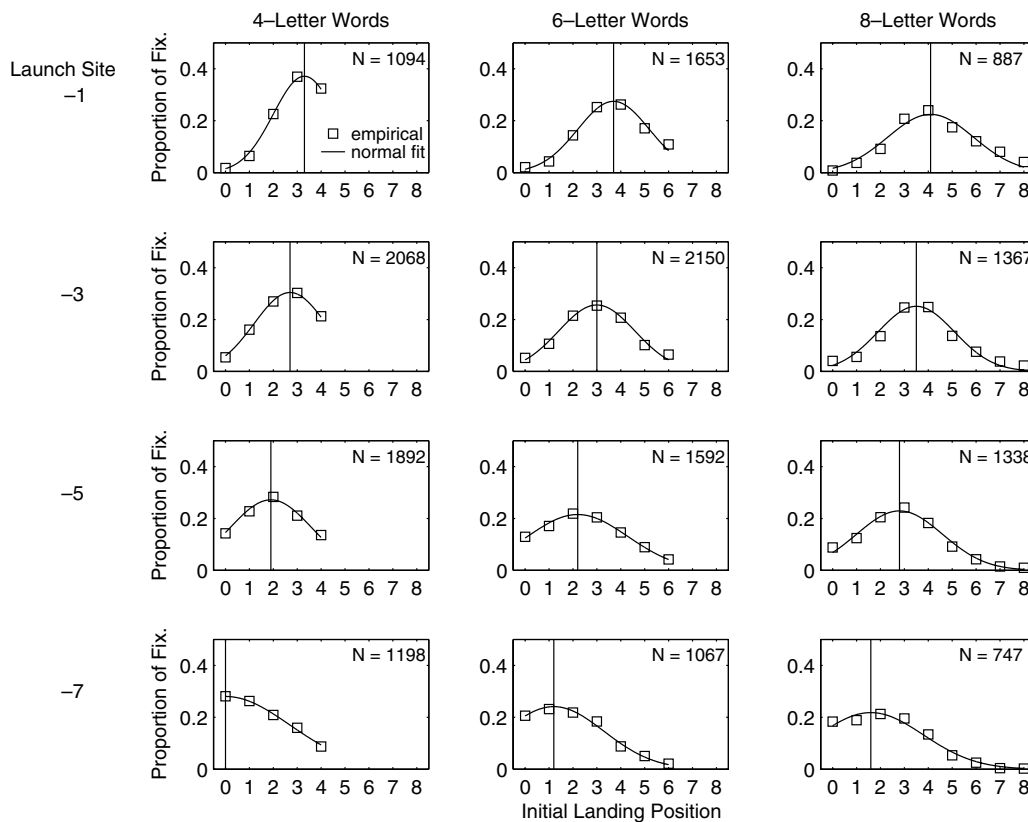

Fig. 6. Landing position distributions for different word lengths and launch site distances. Also presented is the best-fitting normal curve for each distribution. Vertical lines represent the means of the fitted curves.

Table 4
Means and standard deviations (SD) of landing positions distributions, as a function of word length and launch site distance, fitted to the normal curve

Launch site	4-Letter words				5-Letter words				6-Letter words				7-Letter words				8-Letter words			
	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.

3.2. Estimation of the fraction of mislocated fixations from experimental data

We used the composite distributions (Fig. 5) to estimate the amount of mislocated fixations in a first approximation. Specifically, we 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).[4] Thus, words are also fixated, refixated and/or skipped due to oculomotor error. Four important cases of mislocated fixations (Fig. 7) result from undershoot (i.e., failed skipping and unintended refixation) and overshoot (i.e., unintended skipping and failed refixation). If, in principle, saccades are aimed at word centers, mislocated fixations will occur primarily at the beginning and end of words.

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. 5).

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
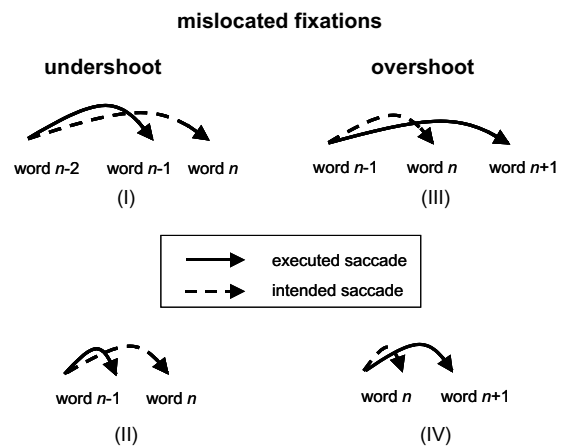

Fig. 7. Four important cases of mislocated fixations. Word n is the intended target word. (I) Failed skipping, (II) unintended refixation, (III) unintended skipping and (IV) failed refixation.

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.

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

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, we applied a grid search method (in steps of 0.1) with a minimum-χ^2 criterion. Best-fitting lines for word lengths from 3 to 8 are shown in Fig. 5; fit parameters are listed in Table 5.

The thin solid line in Fig. 8 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

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[4] 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.

Table 5
Means and standard deviations (SD) of landing positions distributions for different word lengths, fitted to the normal curve

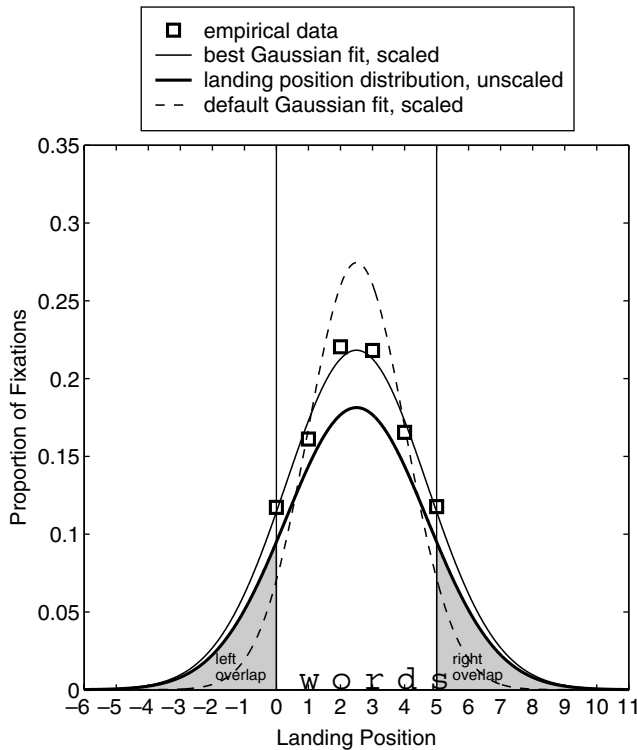| Word length	Mean	SD	Sum of squared residuals	N
3	2.2	2.2	0.00001	28,545
4	2.3	2.2	0.00029	18,966
5	2.5	2.2	0.00030	23,078
6	2.8	2.2	0.00087	19,642
7	2.9	2.3	0.00148	17,726
8	3.2	2.4	0.00193	14,433

Fig. 8. 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 Fig. 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).

that a scaled default normal fit[5] would overestimate the maximum and underestimate the standard deviation of the fitted normal distribution considerably (thin dashed line in Fig. 8). This demonstrates the advantage of the conditional probability density, Eq. (4), with parameters determined with the grid search method.

Second, we assumed—in the sense of a first-order approximation—that empirical landing position distri-

butions consist of well-located fixations only. For an estimate of the proportion of mislocated fixations, we extrapolated the Gaussian distribution $N(\mu_L, \sigma_L; x)$ with mean μ_L and standard deviation σ_L beyond the word borders (bold line in Fig. 8). We used an unscaled normal distribution 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 6–11 (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). 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.

Finally, we estimated the probability $p_L^{\mathrm{mis}}(x)$ that a given word n of length L *receives* a mislocated fixation at letter position x. For example, as illustrated in Fig. 9(a), 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. 5, Table 5),[6]

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

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 $p_L(x|n)$ 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

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[5] We used the Matlab (The Mathworks, Inc.) function 'normfit'. Mean and standard deviation of the normal distribution are computed by using the minimum variance unbiased estimator.

[6] We also computed 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.

Table 6
Probabilities for generating a mislocated fixation and receiving a mislocated fixation as a function of word length

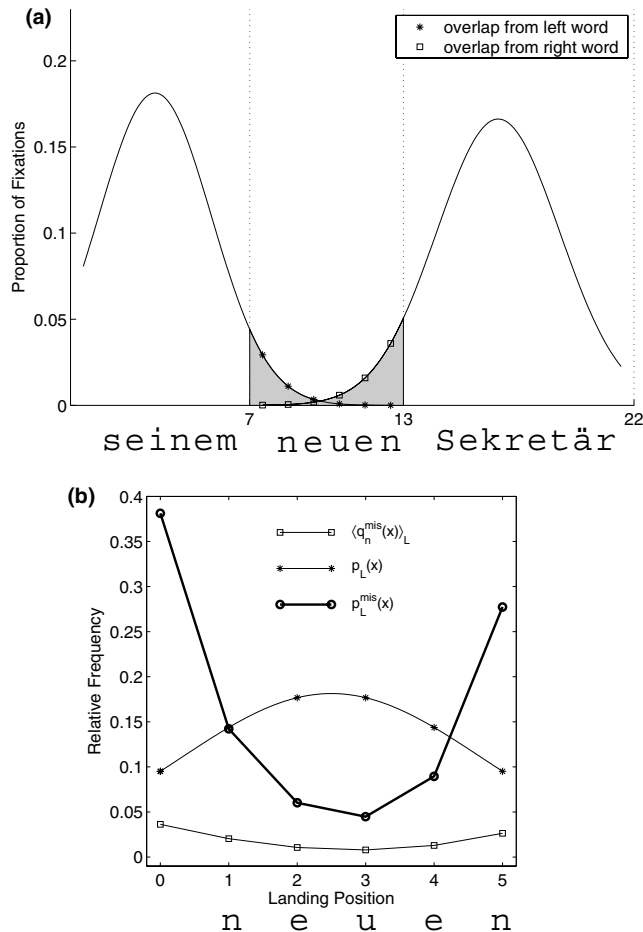| Word length	Generating mislocated fixations			Receiving mislocated fixations
	Left overlap	Right overlap	Sum	
3	0.11	0.28	0.39	0.11
4	0.10	0.16	0.26	0.12
5	0.08	0.08	0.16	0.11
6	0.07	0.04	0.11	0.12
7	0.07	0.02	0.09	0.14
8	0.06	0.01	0.07	0.10

Fig. 9. 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 $\langle q_n^{mis}(x)\rangle_L$ as the proportion of mislocated fixations according to the triplet algorithm and $p_L(x)$, the unscaled landing position distribution.

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, we averaged this probability over all words of a given length L and divided the result by the landing position distribution for words of length L, which yielded the relation

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

where $\langle \cdot \rangle_L$ 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), we computed the overlap word by word on the basis of word triplets; for an illustration see Fig. 9(a). The center word of the triplet 'seinem neuen Sekretär' [his new secretary] is the word 'neuen' [new]. For the center word of every triplet, we computed the overlap from the left and right word respectively. Our analysis is based on distributions for words with lengths ranging from 3 to 8, so we considered triplets where all three words had at least three and not more than eight letters. 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. 9(b) 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). 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. Given the amount of mislocated fixation from overlap, $\langle q_n^{mis}(x)\rangle_L$, we finally computed the proportion of mislocated fixations, $p_L^{mis}(x)$, relative to the Gaussian landing position distributions, $p_L(x)$, according to Eq. (7), see Fig. 9(b) for an example.

Applying this procedure to words of length 3–8 yielded probabilities for mislocated fixations as a function of word length and landing position (Fig. 10(a)). 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, we were able to estimate the probability for mislocated fixations as a function of word length and within-word fixation position.
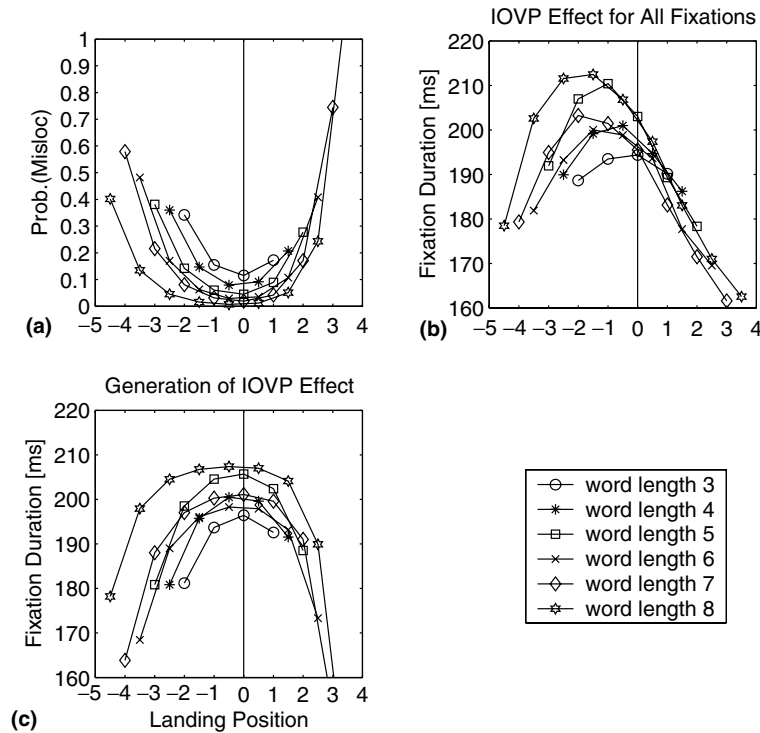
Fig. 10. Error-correction of mislocated fixations as an explanation for the IOVP effect. (a) Proportion of mislocated fixations as a function of word length and landing position. (b) Empirical IOVP effect: The inverted U-shaped curves represent the mean fixation duration (for all fixations except first and last fixations in a sentence) as a function of word length and landing position. (c) Generation of the fixation duration IOVP effect.

3.3. The IOVP effect as a consequence 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, we add some calculations to check the proposed model quantitatively. We assumed that the oculomotor system is able to recognize whether the eye landed on the intended target word or not. The principle of efference copies processed in the brainstem superior colliculus (Carpenter, 2000; Wurtz, 1996) 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, we calculated the fixation duration as a function of landing position according to the mechanism of error-correction of mislocated fixations. For simplicity, we 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

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

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. 10(c), we used a value of $\tau_C = 125$ ms.[7] 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.

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. 10(b)) was stronger for fixations at the end of words; fixations on the 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. 10(a)). This asymmetry of the IOVP effect could be reproduced for 7- and 8-letter words only. Furthermore, for most word

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[7] 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.

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.

4. Discussion

We proposed a mechanism underlying the IOVP effect for fixation durations, that is the effect that fixation durations near word boundaries were considerably shorter than fixation durations close to word center. Our theoretical explanation was developed in two steps. First, we 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 we demonstrated that our 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.

4.1. IOVP effects and mislocated fixations

4.1.1. IOVP effects

Based on the analysis of data obtained for a German sentence corpus, we replicated Vitu et al.'s (2001) fixation duration IOVP effect for both single and first fixations. 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 20–40 ms for single fixations, and up to 80 ms for first fixations. Extending the pioneering work by Vitu et al. (2001), we provided a better mathematical description of the IOVP effect by fitting the data to a quadratic function, i.e. a polynomial of second-order. Corresponding parameters facilitated interpretation of data obtained for different word lengths. We demonstrated that the strength of the experimentally obtained IOVP effect increases with word length, a finding that is compatible with the mechanism assumed to be responsible for the effect.

4.1.2. Mislocated fixations

We distinguished four important cases of mislocated fixations (Fig. 7): failed skipping, unintended refixation (both undershoot), unintended skipping, and failed refixation (both overshoot). 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 (III), 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 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 refixation failed (case IV) if the eye did not—as intended—land on the launch word (n), but on the word to the right of the launch word (n + 1).

4.2. Coupling saccade programs to oculomotor errors

4.2.1. Oculomotor errors

For our theoretical explanation of IOVP effects, we needed precise estimates of oculomotor errors, which produce—when large enough—mislocated fixations. We replicated McConkie et al.'s (1988) empirical findings on systematic oculomotor errors (saccadic range error). 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 6–7 letters for English data.

4.2.2. Estimation of the fraction of mislocated fixations

We developed an algorithm for the estimation of the fraction of mislocated fixations as a function of word length and within-word fixation position. On the assumption of Gaussian distributed landing positions, we extrapolated the experimentally obtained distributions from within-word landing positions to neighboring words. The fraction of mislocated fixations was then computed as the proportion of overlapping probability relative to landing site probability. According to our calculations, more than 10% of all fixations could be mislocated. 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. These results suggest that mislocated fixations might be very frequent and should not be neglected in data analysis and theoretical models.

4.2.3. An explanation for IOVP effects

As a new central theoretical claim, we suggest 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, we provide a possible explanation for an effect which Vitu et al. (2001) concluded to be elusive.

The overall probability of receiving a mislocated fixation was similar for all word lengths considered (Table 6). Fig. 10(a) 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 our 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. 10(b)) and generated (Fig. 10(c)) data. Mathematically, this relationship was captured by parameter B' which systematically increased with word length (see Table 2 for empirical data).

In principle, every fixation can be a mislocated fixation. Thus, our mechanism predicts an IOVP effect for single-fixation, first-fixation, and second-fixation durations, and that is what we observed. Given the available data, our approximations, however, do not allow us to reproduce quantitative differences between these IOVP functions, such as the stronger curvature for first of two compared to single fixations. We argue that the mechanism is an important part of the explanation of the IOVP effect; it may not be the sole explanation, as we cannot account for an IOVP effect for first-fixations durations in two-fixation cases, obtained in an isolated word recognition paradigm (O'Regan & Lévy-Schoen, 1987).

4.2.4. 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 (e.g., see Rayner, Warren, Juhasz, & Liversedge, 2004, proposing that mislocated fixations which undershot the intended target word contribute to parafoveal-on-foveal effects). Obviously, removing or reassigning mislocated fixations could substantially increase the statistical power for detecting experimental effects.

4.3. Implications for theoretical models of eye-movement control

Current theories on eye-movement control in reading neglect 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 we 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., Engbert et al., 2002; Reichle et al., 2003) 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), however, the occurrence of mislocated fixations itself might significantly impact upon the reading process. 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, we believe 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). If our estimates in the order of 10% mislocated fixation are valid, this would imply roughly more than one mislocated fixation per sentence. We would argue that this is not a small percentage. 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 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.

In an alternative model of eye-movement control, called SWIFT (Engbert et al., 2002; Engbert, Nuthmann, Richter, & Kliegl, submitted for publication; Kliegl & Engbert, 2003), we 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.

In the current paper, we replicated IOVP effects for fixation durations in reading. We explain the effect as a consequence of mislocated fixations caused by saccadic errors. The proposed mechanism for generating the effect is generally compatible with both oculomotor and cognitive models of eye-movement control in reading. We conclude that the IOVP effect for fixation durations might evolve into an important boundary condition for computational models of eye-movement control during reading.

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