Mixed Responses: Why Readers Spend Less Time at Unfavorable Landing Positions

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This paper investigates why the average fixation duration tends to decrease from the center to the two ends of a word. Specifically, it examines (a) whether unfavorable landing positions trigger a corrective mechanism, (b) whether the triggering is based on the internal efference copy mechanism, and (c) whether the corrective mechanism is specific to fixations that missed their targeted words. To estimate the mean and proportion of the corrective fixations, a 3-parameter mixture model was fitted to distributions of first fixation duration from two large eye movement databases in studies 1 and 2. Study 3 experimentally created mislocated fixations using a gaze-contingent screen shift paradigm. There is little evidence for the efference copy mechanism and limited support for the mislocated fixations hypothesis. Overall, data suggest a process that terminates fixations sooner than would during normal reading; it is triggered by the visual input during a fixation, and is flexibly engaged at eccentric landing positions and in reading short words. Implications to theories of reading eye movements are discussed.

Introduction

The eyes sometimes make surprising moves during reading. It is well known that when the eyes land on a position that is far away from the center of a word, the speed and accuracy of word recognition takes a toll (e.g.,O'Regan & Jacobs, 1992; O'Regan, Levy-Schoen, Pynte, & Brugaillere, 1984; Vitu, O'Regan, & Mittau, 1990). Thus one would expect the eyes to stay longer at these unfavorable landing positions to compensate for the loss of efficiency. But instead, the average duration of the first fixation is shorter at these unfavorable locations than near the word center (Nuthmann, Engbert, & Kliegl, 2005; Nuthmann, Engbert, & Kliegl, 2007; O’Regan, Vitu, Radach, & Kerr, 1994; Vitu, Lancelin, & Marrier d'Unienville, 2007; Vitu, McConkie, Kerr, & O'Regan, 2001). Why?

The present paper tries to shed some light on this paradoxical phenomenon – also known as the inverted optimal viewing position (IOVP) effect – by analyzing the distribution function of fixation duration. More specifically, the paper attempts to answer (a) if the IOVP effect is caused by a corrective mechanism distinct from normal reading, (b) whether it is in response to fixations that accidentally missed their intended targets, and (c) whether the correction is triggered by retinal input or by the internal efference copy mechanism. I will briefly review current theories of the phenomenon and discuss the rationale for the distributional analysis before presenting three empirical studies.

The OVP and the Inverted OVP Effect. The optimal viewing position (OVP) is the letter position in a word that, when fixated, yields the fastest and most accurate word recognition (O'Regan, 1990; O'Regan & Jacobs, 1992; O'Regan, et al., 1984). The OVP is found to be slightly to the left of the center of the word in English (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989) and French (O'Regan, et al., 1984). When the initial landing position is away from the OVP, word processing is slower and less accurate (e.g.,O'Regan & Jacobs, 1992; O'Regan, et al., 1984; Vitu, et al., 1990). In studies using words in isolation, it is estimated that the penalty for eccentric viewing position is around 20-30msec per letter space from the OVP (O'Regan, 1990). In natural reading, unfavorable locations cause elevated gaze duration

(O'Regan, et al., 1984) and an increasing rate of refixations (McConkie, et al., 1989).

However, a different pattern emerges when only the first fixation on a word is considered: the first fixation duration is *shorter* at either end of the word and *longer* at the OVP (Nuthmann, et al., 2005; Nuthmann, et al., 2007; O'Regan, et al., 1994; Vitu, et al., 2007; Vitu, et al., 2001). This IOVP effect seems counterintuitive: it allocates less processing time when more is needed. Several models have been proposed to explain the paradoxical IOVP effect.

The Mislocated fixations hypothesis. Nuthmann and colleagues (Nuthmann, et al., 2005; Nuthmann, et al., 2007) argue that the shorter fixation duration is due to automatic corrections of oculomotor errors. According to this view, some saccades miss their target word and ended up on words before or after it. These *mislocated fixations* are bound to happen due to oculomotor noises (McConkie, Kerr, Reddix, & Zola, 1988), and they occur more frequently near the edges of words (Engbert, Nuthmann, Richter, & Kliegl, 2005; Nuthmann, et al., 2005; Nuthmann, et al., 2007). Once the error is detected, it is assumed that a saccade is automatically programmed, and the saccadic delay is much shorter than typical reading eye movements. Thus the average fixation duration will be shorter at eccentric locations than the OVP. This is implemented in the SWIFT model (Engbert, et al., 2005; Nuthmann & Engbert, 2009) as the primary explanation for the IOVP effect.

The mislocated fixations hypothesis predicts a mixture of two distinct distributions of fixation duration, one for normal reading eye movements and the other for eye movements associated with mislocated fixations. The detection of mislocated fixations is hypothesized to be based on the *efference copy* mechanism, whereby the oculomotor system uses internal representations of the saccadic target and the oculomotor trajectory to predict the end location of the saccade (Engbert, et al., 2005; Nuthmann, et al., 2005; Nuthmann, et al., 2007). This allows the oculomotor system to determine if the saccade will miss the target word during the saccade, without any visual feedback. If a mislocated fixation is to occur, a saccade is programmed immediately at the onset of the subsequent fixation. It is important to note that the saccade is not necessarily directed to the original target of the mislocated fixation (Engbert, et al., 2005). Instead, it is subject to the same probabilistic saccadic targeting mechanism as regular reading eye movements. In the context of this paper, however, I will refer to them as part of a corrective mechanism, only in the sense that they are initiated in response to oculomotor errors. Unlike in other theories, the corrective response is triggered because the saccade misses the intended target, not because the fixation landed on an unfavorable position on a word.

The E-Z Reader model. The E-Z Reader model (Pollatsek, Reichle, & Rayner, 2006) also includes an error correction mechanism that produces shorter saccadic delays at eccentric within-word fixation locations. It is assumed that a refixation is programmed automatically, and the probability of initiating the corrective refixation increases with the distance from the OVP (Pollatsek, et al., 2006). The automatic refixation mechanism competes with the lexically based saccadic triggering mechanism. Saccades triggered by the refixation process tend to occur earlier than lexically triggered saccades because they do not involve linguistic processing. On the other hand, within lexically triggered eye movements, the fixation duration should be longer at eccentric locations than those at the OVP because eccentricity slows down lexical processing (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2006; Reichle, Rayner, & Pollatsek, 2003). The lengthening effect is nevertheless overpowered by the effect of the automatic refixation mechanism, resulting in shorter mean fixation durations at eccentric positions.

As with the SWIFT model, E-Z Reader explains the IOVP effect in terms of a mixture of two processes – a corrective mechanism versus normal reading. However, there are important differences between the two models. First, in SWIFT the error correction is specific to mislocated fixations, whereas in E-Z Reader it is triggered by unfavorable landing positions. Second, the corrective saccade target different words. Whereas in E-Z Reader a correction is always targeting the OVP, in SWIFT saccades triggered by mislocated fixations may target the same word or a different word. Finally, SWIFT relies primarily on the fast efference copy mechanism (Engbert, et al., 2005; Nuthmann, et al., 2005; Nuthmann, et al., 2007), which does not require input from the retina; E-Z Reader's error correction is based on the visual input from the current fixation (Pollatsek, et al., 2006), and thus would have to include the 50-90msec eye-brain lag (e.g., Pollatsek, et al., 2006; Reichle, et al., 2006; Sereno & Rayner, 2003).

The SERIF model. A vertically split fovea is part of the basic physiology of the human vision system. Letters falling to the left and right visual fields are projected countralaterally to the right and left visual cortex, respectively. According to the SERIF model (McDonald, Carpenter, & Shillcock, 2005), each hemisphere retains independent but partial representations of the word, and each attempts to identify the word independently. Skilled readers generally prefer to balance lexical uncertainties in the two hemispheres by fixating near the OVP (McDonald & Shillcock, 2005). The SERIF model further assumes that a saccade may be triggered independently by either hemisphere. The competition between the two hemispheres is a key to the IOVP effect: fixations on the OVP have balanced left vs. right hemisphere activations. Compared to eccentric locations, the saccadic decision takes longer to reach at the OVP due to a stronger lateral inhibition (McDonald & Shillcock, 2005).

Unlike SWIFT and E-Z Reader, SERIF relies on a single mechanism to account for the IOVP effect. The temporal aspect of the SERIF is modeled by two LATER models for the two hemispheres (Carpenter & Williams, 1995; Carpenter & McDonald, 2007). The LATER model assumes that during a fixation information accumulates linearly toward a fixed threshold, and a saccade is triggered when the threshold is reached. In SERIF, lateral inhibition is tied to the rate of information accumulation (Reddi, Asrress, & Carpenter, 2003) such that the rate is higher for eccentric locations than word-central locations. This translates to a higher concentration of short fixations at unfavorable locations, and consequently shorter average fixation duration.

The perceptual-economy hypothesis. Vitu and colleagues (2007) proposed the perceptual-economy hypothesis, which argues that the IOVP effect is a learned oculomotor strategy. Specifically, longer duration is planned for fixations near the OVP where a greater amount of information is anticipate, and conversely, shorter fixations are allocated to non-optimal viewing locations (Vitu, et al., 2007). This heuristic is acquired through experience, and is triggered by low-level perceptual information, without expensive on-line computations. Although not as fleshed out as other theories, the functional perspective is informative and promising.

In sum, current theories differ in a number of key issues. First, theories disagree on whether the IOVP effect is the result of a single mechanism (e.g., SERIF) or a mixture of two mechanisms – normal reading and corrective eye movements (e.g., SWIFT and E-Z Reader). Second, among the proponents of corrective saccades, SWIFT is triggered by mislocated fixations and E-Z Reader corrects eccentric fixations without regard to their original targets. Third, the two theories also differ on whether retinal input is required to detect oculomotor errors. Finally, most current theories focus on potential neurocognitive mechanisms underlying the IOVP effect, to date only Vitu et al (2007) explicitly addressed the question of what gives rise to these mechanisms in the first place. It may be the case that the IOVP effect is simply a manifestation of the workings of the reading apparatus. But if it is a means to achieve better reading, then a coherent theory of reading eye movement must include a developmental narrative, i.e., what the initial state of the system is and how it is optimized for proficient reading.

Distributional Analysis of Reading Fixation Duration

If, as SWIFT and E-Z Reader predict, saccades from unfavorable landing locations are triggered by two separate stochastic mechanisms (i.e., normal reading vs. corrective), the observed distribution of fixation duration should be a weighted average of the two component distributions. Under some conditions, the empirical distribution function can be mathematically decomposed to reveal the original components.

Mixture modeling. Assume that fixations at a landing position L are triggered by two independent mechanisms, N (for normal reading) and C (for the corrective process), and the duration of these fixations follow two distinct probability density functions (*pdf*'s), $f_N(x)$ and $f_C(x)$. The *pdf* of the combined distribution is

$$f_L(x) = (1-w)\cdot f_N(x) + w\cdot f_C(x)$$

where w is the unknown proportion of fixations generated by the mechanism C. More generally, for a mixture of n components, each with weight w_i, $\sum_i w_i = 1$, the mixed distribution is

$$f_L(x) = \sum_i w_i \cdot f_i(x)$$

In the case where both $f_N(x)$ and $f_C(x)$ are known, it is straightforward to estimate w by fitting the function to an empirical frequency distribution. When $f_N(x)$ and $f_C(x)$ involve free parameters (e.g., unknown means and/or variances) it is often computationally intensive to simultaneously estimate the weights and parameters. Fortunately, efficient and robust algorithms exist for mixtures of well-known theoretical distributions such as the normal distribution and lognormal distribution. These algorithms typically involve numerical techniques such as hill-climbing or expectation-maximization; to avoid local maxima, multiple starting values are used in the present study for parameter estimation. The present study involves very large samples and less than a handful of free parameters, and models consistently converge to globally optimal solutions.

The SHARE model. An example of mixture modeling in eye movement research is the *Stochastic, Hierarchical Architecture of Reading Eye-movement* (SHARE), a general-purpose Bayesian statistical model for reading eye movements (Feng, 2001, 2003, 2006a). Feng (2006) showed that a mixture of three lognormal components can account for a wide range of empirical distributions from adult and child readers. Essentially, one component distribution captures the left tail of the distribution where there is often a "bump" of very brief fixations, another fits the long right tail, and the third distribution accounts for the main peak of the distribution, typically around 180msec. The choice of the lognormal distribution was motivated by its unimodal hazard function, which resembles the hazard function of empirical reading fixation durations (Feng, 2009). The model involved eight free parameters (three means, three standard deviations, and two weights). A Bayesian approach was used to estimate the parameters. SHARE was designed to maximize the fit to observed distributions, and thus has few restrictions on the values of the parameters.

The restricted mixture model. The current study has a different goal. While the overall goodness of fit is still important, the focus here is to estimate the *C* component and compare its parameters at different landing positions. Obviously, it is meaningless to compare a parameter while all other parameters co-vary. The solution is to fix as many parameters as possible, while still maintaining good overall fit. Five of the eight parameters in SHARE will be fixed in the present study, leaving only three free parameters. The model is expected to fit less well compared to the full SHARE model, but the trade-off is necessary to compare parameters of interests across landing positions.

The values of the free parameters depend on values of the fixed parameters. A simple heuristic is used in the current study to assign the fixed parameters. Since both E-Z Reader and SWIFT models suggest that the OVP has the fewest corrective saccades, the mean and standard deviation of the *N* component are chosen so that w_C is as small as possible at the OVP. Pilot studies show that a two-component model (i.e., with only the *C* and *N* components) is unable to account for the brief fixations at the left tail of the distribution. Like the original SHARE model, the model also includes an *E* component (for early saccades), a lognormal distribution with a mean of 85msec and standard deviation of 30msec. Variations in brief fixations will be captured by the weight of the *E* component. The standard deviation of the corrective component is set to 30msec, based on pilot runs of the model. Under these constraints, any differences in distributions of first fixation duration must be accounted for by the mean and proportion of the *C* component, and the proportion of the *N* component.

The Present Study

This paper reports three studies based on two large corpora of reading eye movements. Study 1 analyzes distribution functions based on data from the Dundee English reading corpus. Study 2 replicates the previous study using a different dataset. Study 3 focuses on a subset of data from study 2 that involved a gaze-contingent display change manipulation – during selected saccades, texts on the screen were shifted horizontally, creating artificial saccadic errors. Together these studies test a couple of predictions based on current theories of the IOVP effect:

1). The corrective fixations model predicts that reading eye movements may be generated by a corrective mechanism in addition to normal reading. Corrective fixations should be shorter than normal reading fixations, and their proportion should increase with eccentricity. The mixture model introduced above is a straightforward way to test this hypothesis.

2). The efference copy hypothesis promises very fast saccadic response times, probably in the range of 100msec or below. A visual-based strategy, on the other hand, is subject to the eye-brain lag and is expected to peak at approximately 120-190msec. The former will be captured in the distribution model by the *E* component and the latter by the *C* component. In the context of gaze-contingent screen shifts, the efference copy theory predicts that the proportion of corrective saccades should be a function of the *pre-shift* landing position, whereas according to the visually based model, the proportion of corrections should be a function of the *post-shift* landing position.

Study 1. The Dundee Corpus

This study estimates the mean and proportion of the *C* component in empirical distributions of first fixation duration at various landing positions. Data come from the Dundee English reading corpus (Kennedy & Pynte, 2005; see also Pynte & Kennedy, 2006), a publically available dataset that has been studied by various research groups (Carpenter & McDonald, 2007; Feng, 2009; Kennedy & Pynte, 2005; Pynte & Kennedy, 2006).

Method

The Dundee English Corpus. Eye movements were recorded from 10 native English speakers from the UK reading approximately 20 newspaper editorials (about 2,800 words each). Participants answer a multiple-choice question after each text. Together the data contain approximately 500,000 fixations. The large dataset allows robust estimation of the mixture model at various landing positions.

A Dr. Bouis system was used to record the eye movements. It sampled at 1000Hz, with a resolution of approximately 0.25 letter spaces. Fixations were detected using a custom-made algorithm that clusters and merges samples of gaze locations into fixations (see Kennedy & Pynte, 2005). Because of clustering and merging, the effective resolution of the Dundee corpus is about one letter position (Kennedy & Pynte, 2005).

Data selection and coding. This study focuses on the first fixations on a word; refixations and regressions were excluded in the analyses. Also excluded were fixations on words shorter than 3 letters or longer than 8 letters. A stronger IOVP effect is expected for even longer words, but the number of fixations on words longer than 9 letters was inadequate for the kind of analyses conducted below. The coding for landing position in the Dundee corpus includes a half letter space before the first letter position and a half letter space after the last letter. For example, landing positions range from 0 to 6 for a 6-letter-long word. This is important for understanding the figures, though it has no practical effect on the results.

In addition, fixations were classified into three categories based on the nature of the subsequent saccade: the *+forward* fixations are followed by saccades that bring the eyes to a new word to the right of the current word; *+refixation* fixations are followed by saccades ending on the same word; and *+regression* fixations are followed by saccades that take the eyes to a word to the left of the current word. The “+” sign highlight the fact that these were first fixations on words but were *followed by* different kinds of saccade. Previous research distinguished between *single fixations* and *first-of-multiple fixations* (e.g., Rayner, Sereno, & Raney, 1996; White, 2008). The latter corresponds to the *+refixations*, and the former is separated into *+forward* and *+regression* fixations in the present analysis. By separating the logically heterogeneous responses, the hope is to shed more light on the IOVP effect of single fixation duration.

Mixture modeling. The present study uses a restricted mixture model with lognormal components. Following the heuristic outlined before, the mean and standard deviation parameters for the *N* component were estimated and fixed. The final model to be estimated at landing position *L* is:

$$f_L(x) = (1 - w_C - w_N) \cdot f_E(x) + w_N \cdot f_N(x) + w_C \cdot f_C(x)$$

where $f_L(x)$ is the *pdf* of the first fixation duration distribution at landing position *L*,
$f_E(x)$ ~ lognormal(85, 30), $f_N(x)$ ~ lognormal(220, 60), and $f_C(x)$~ lognormal(μ_C, 30); w_N and w_C are weights for the normal reading and corrective components, respectively. There are three free parameters to be estimated from data, i.e., μ_C, w_N, and w_C.

Modeling of fixation duration distributions was conducted in *R* v2.7.2 (R Development Core Team, 2008). Mixture modeling was done with the *R* library *mixdist* (Du, 2002), an *R* adaption of the original MIX algorithm (McDonald, 1987). Both *R* and *mixdist* are open source and are available for free download. The script for mixture estimation is available upon request.

Observed first fixation durations were divided into twenty-seven 20-millisecond bins and two catchall categories, one for fixations shorter than 60msec and the other for fixations longer than 600msec. The MIX algorithm then searches for the optimal combination of parameters (μ_C, w_N, and w_C) that maximizes the fit between the mixture model and the empirical histogram. Estimations were carried out with different initial values (e.g.,

μ_C=160, w_C=0.1, and w_N =0.8) and they routinely converged on the same solutions.

Results

The IOVP effect. Figure 1 shows the mean fixation duration as a function of landing position, word length, and the type of subsequent saccade. The left panel, which shows the unconditioned means, replicates the IOVP effect reported in previous studies (Nuthmann, et al., 2007; Vitu, et al., 2007; Vitu, et al., 2001). For words longer than 5 letters, the mean first fixation duration is highest near the center of the word but decreases in eccentric landing positions. Analyses of variance showed that the first fixation duration differed significantly as a function of landing position at all word lengths (all *F's*>10, *p's<0.001*) except for 3-letter words, *F(3,29550)=3.102, p=.026*, not significant after Bonferroni adjustment with six comparisons. The quadratic trend was highly significant for long words: for 6-letter words, *F(1,25993)=23.749, p<.001*, for 7-letter words, *F(1, 26710)=50.643, p<.001*, and for 8-letter words, *F(1,18603)= 108.221, p<.001.*

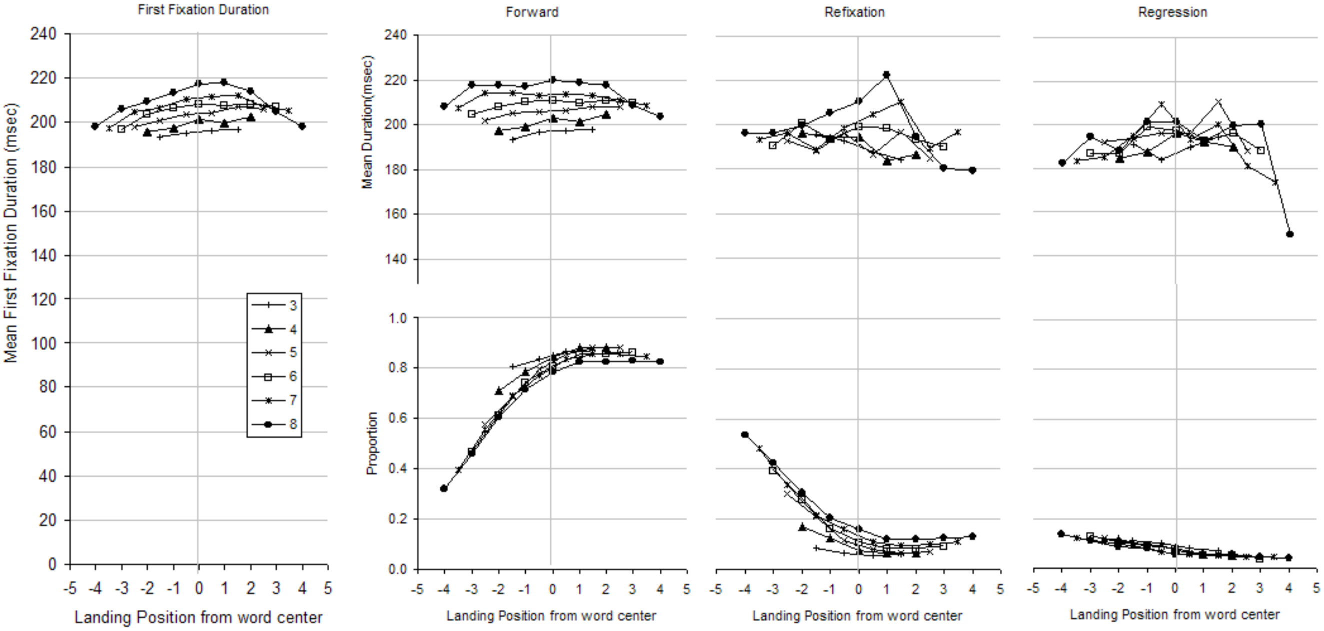

Figure 1. The IOVP effect in Dundee Corpus (left panel), and its breakdown by the type of subsequent saccades. The top panels on the right show the mean duration of +forward, +refixation, and +regression fixations. The corresponding bottom panels show the proportion of the said fixations at each landing position.

The right panels of Figure 1 separated the data by the type of the saccade that followed the current fixation. The top panels show the average first fixation duration of *+forward, +refixation,* or *+regression* fixations, respectively. The mean duration of the *+forward* fixations resembles that of Figure 1, but the IOVP effect is severely attenuated: except at the first and last letters, the average first fixation duration appears to be largely invariant with the landing position. Mean durations for *+refixation* and *+regression* fixations show more fluctuations, due to smaller sample sizes, but on average they are shorter than *+forward* fixations.

The bottom panels illustrate the proportion of *+forward, +refixation,* or *+regression* fixations, respectively, at each combination of word length and landing position. The proportions explain part of the overall IOVP effect. While in most cases the majority of first fixations were *+forward* fixations, the probability is dramatically lower for far-left landing positions. Correspondingly there is an increase in the probability of +*refixation* and +*regression* fixations, which tend to be shorter than +*forward* fixations. The probabilities do not explain, however, why the mean first fixation durations were lower on the right side of the word. The next set of analyses will decompose distributions of first fixation duration into mixture components and explore if the *C* component is responsible for the decrease of fixation duration on the right hand side of the word.

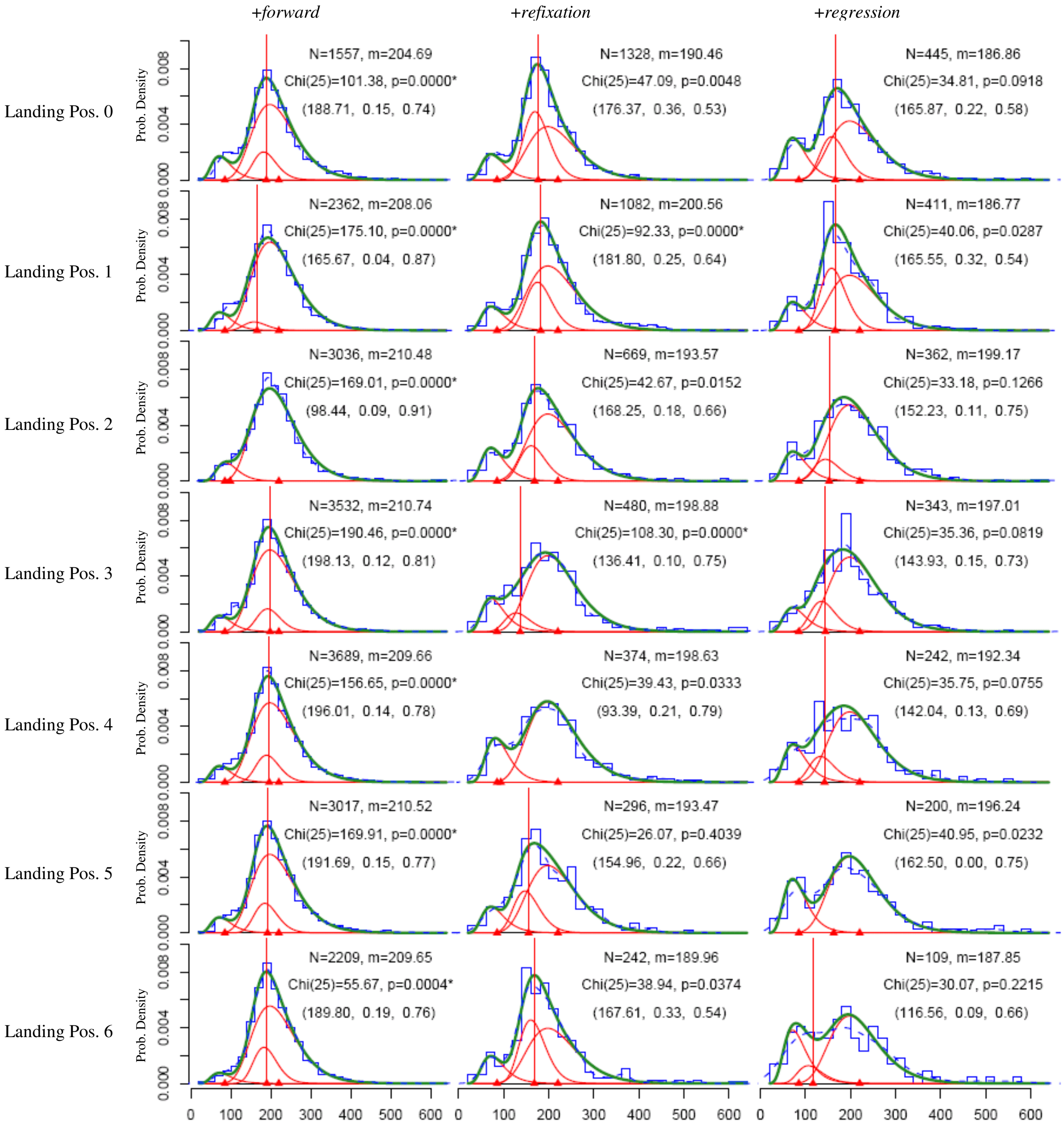

Figure 2. Illustration of the goodness of fit of the 3-parameter mixture model for Dundee Corpus, 6-letter words, by landing position and type of the next saccade. The vertical line indicates μ_C. μ_C is also shown in the parentheses, along with w_C and w_N.

Mixture modeling: an illustration. The 3-parameter mixture of lognormal model was fitted to the distribution of first fixation duration at each combination of word length, landing position, and type of the next saccade. Figure 2 illustrates the 21 distributions for 6-letter-long words. All 117 distributions from the Dundee corpus can be found in the supplemental materials.

The three columns represent the *+forward, +refixation,* or *+regression* fixations, respectively. Each row corresponds to a landing position (from 0 to 6), with position 3 being the center of the word. In each plot, a histogram of the observed first fixation duration is plotted with a bin-width of 20msec. The dash line represents the estimated empirical *pdf* based on kernel density estimation (the "density" function in R, R Development Core Team, 2008) with a Gaussian kernel and a bandwidth determined according to Silverman (1986). Overlaid on the empirical distribution are the mixture model *pdf* (bold line) and the three component lognormal distributions scaled by their corresponding weights. That is, all things being equal, a component with larger weight is "taller" than one with smaller weight. In a few cases some components had zero weight and cannot be seen in the plots. The mean of the three components are marked with triangles on the x-axis; a vertical line represents the mean of the *C* component if its weight is larger than 1%. Occasionally, when $f_N(x)$ adequately accounts for the body of the distribution, the *mixdist* algorithm uses the free parameter in $f_C(x)$ to improve the estimation of the *E* component, in which case μ_C is close to or less than 100msec and is not marked with a vertical line. The sample size, mean fixation duration, and the value of the three parameters (mean and weight for the corrective component and the weight for the normal reading component, respectively) are shown in each plot.

It is important that the restricted 3-parameter mixture model adequately captures the range of empirical distributions from the corpus. A visual inspection of Figure 2 suggests that the mixture model strikes a good balance between model fit and parameter estimation. Despite having only three free parameters, the mixture model captures important features of the distribution, such as the initial "bump" of brief fixations, the long tail, and the location and shape of the peak. In general, the model is successful in modeling the long tail of empirical distributions with the fixed *N* component, $f_N(x)$ ~ lognormal(220, 60). The combination of the *C* and *N* components also captures the varying location and kurtosis of the mode. The fixed *E* component, $f_E(x)$ ~ lognormal(85, 30), accounts for most variations in the left tail of the distribution, although the 3-component model occasionally have troubles with the juncture between *E* and *C* components. This systematic deviation is reflected in Chi-square tests of the goodness of fit of the model, which are shown in the plots. With large sample sizes (e.g., $n>1,000$), the Chi-square test consistently rejects the mixture model. When the sample size was in the hundreds, though, the Chi-square statistics was often non-significant. It is well-known (e.g., Van Zandt, 2000) that Chi-square is a problematic goodness-of-fit index because it tends to reject models with a sufficiently large *N*. For example, there is no evidence that models rejected by the Chi-square test in Figure 2 are any more deviant than models with insignificant results. For the purpose of estimating the mean and weight of the *C* component, the simple 3-parameter model appears to provide a useful, though imperfect, description of a wide variety of empirical distributions.

Moreover, the heuristics of assigning the fixed parameters also seem to have succeeded. As seen in Figure 2, the proportion of the *C* component is low near the OVP. In a number of cases, the two fixed components, $f_N(x)$ and $f_E(x)$ fully accounted for these empirical distributions. Because the means and variations of these two components are constant for all analyses, any distributional differences across landing positions must be attributable to the three free parameters, μ_C, w_N, and w_C, which will be examined in turn.

The μ_C parameter. The parameter μ_C is the mean of the *C* component, the hypothesized corrective eye movements; the standard deviation of *C* is fixed at 30msec. The top panels of Figure 3 show μ_C as a function of landing position, word length, and type of subsequent saccades. In 3 cases the estimate was below 100msec. These occurred when the corresponding weight for the *E* component was zero (see the second row in Figure 3); essentially the *mixdist* algorithm determined the most profitable way to use the free parameter μ_C was to replace the $f_E(x)$ distribution. They remain on Figure 3 to illustrate the number of such cases, but they should be discounted in understanding the behavior of the μ_C parameter.

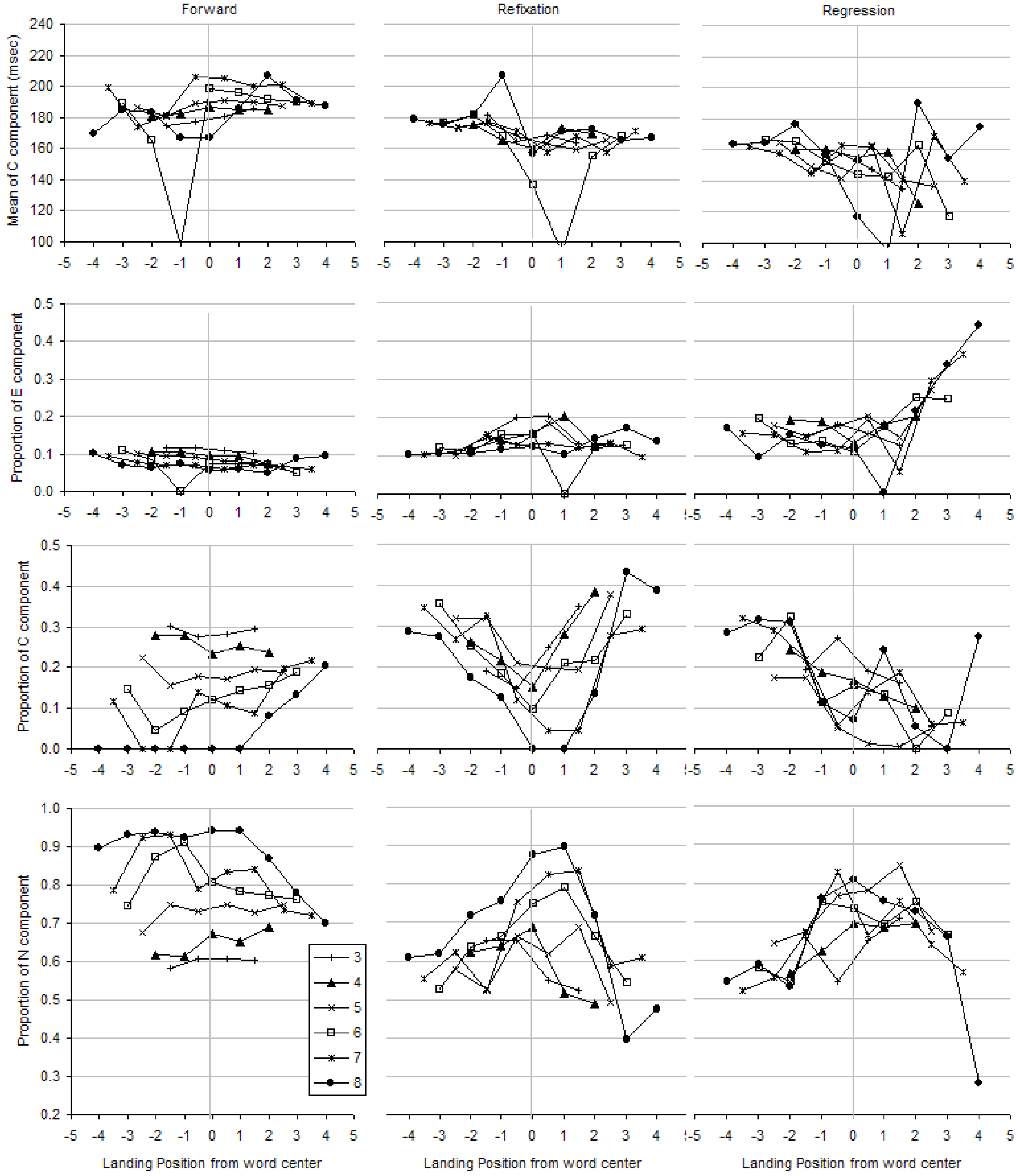

Figure 3. Estimates of μ_C (1st row), w_E (2nd row), w_C, (3rd row), and w_N (4th row) parameters based on the Dundee corpus.

Ignoring these three cases, a number of observations can be drawn from the figures. First, on average the μ_C parameter decreases in the order of *+forward*, *+refixation*, and *+regression*. Second, whereas it seems to increase with landing position in the case of *+forward*, it generally decreases for *+refixation*, and *+regression* cases. Finally, there is little evidence of word length effect. Linear regressions with μ_C as the dependent variable and word length and landing position as independent variables largely confirmed these observations. The intercepts at landing position of zero were 181.26, 163.15, and 138.95msec for the *+forward*, *+refixation*, and

+regression fixations, respectively. The corresponding unstandardized regression coefficients for landing position were 2.01, -2.29, and -2.44msec/letter; the first two regression coefficients were statistically significant, *t(35)=2.619, p=0.013*, and *t(35)=-2.944, p=0.006*, although the last coefficient was only marginally significant, *t(35)=-1.888, p=0.067*. Finally, in no case was word length a significant predictor of μ_C: for *+forward* fixations, *t(35)=.939, p=0.354*, for *+refixations*, *t(35)=1.116, p=0. 272*, and for *+regressions*, *t(35)=-1.392, p=0.173*.

The weight of the E component. Although not an independent parameter because w_E+ w_C+ w_N =1, the weight of the *E* component is theoretically important. If corrective saccades are triggered by the efference copy mechanism, the saccadic response time is expected to be less than 100msec, and therefore should be reflected in the w_E parameter. Additionally, the mislocated fixations hypothesis predicts a U-shaped function of w_E, i.e., more corrective fixations at eccentric landing positions than near the OVP.

This was clearly not the case. The second row in Figure 3 shows the estimated w_E parameter as a function of landing position, word length, and type of subsequent saccades. Ignoring cases when it was zero (see discussion above), there is little evidence of a U-shaped function for *+forward* fixations or *+refixations*. If anything, the *+regressions* exhibit an increase of the proportion of *E* component near the right edge of words longer than 5 letters. However, Figure 1 shows there are very few first fixations that landed on the right end of long words and preceded regressions. These estimates are typically based on less than a hundred fixations and are not as reliable as those based on thousands of fixations.

Weights of the C and N components. Because there are few systematic changes in w_E, the parameters w_C (row 3) and w_N (row 4) appear to be mirror images, and therefore we will discuss them together. Looking at the *+forward* fixations, both w_C and w_N showed a profound word length effect that mirror the IOVP effect in Figure 1. For words 6 letters or longer, there was a substantial increase of w_C on right side of the word and, correspondingly, a decrease of w_N. Because both the mean and standard deviation of *C* is smaller than *N*, this explains the right side of the IOVP effect in Figure 1: unlike the left side, where the IOVP is primarily caused by elevated proportions of refixations and regressions, the IOVP to the right of the word center is mostly driven by a shift in the fixation duration distribution, i.e., a systematic increase in the *C* component.

Discussion

The present study directly estimated the proportion and timing of corrective saccades as a function of landing positions. This is achieved with a highly constrained log-normal mixture model. A number of observations are interesting in the light of current theories of the IOVP effect.

First, the simple mixture model successfully accounts for a wide range of empirical distributions. This strengthens the argument for multiple saccade triggering processes during reading. While a single-process model may be able to account for these diverse empirical distributions, the fact that only three free parameters are needed in the present model speaks to the parsimony of the mixture model and the dual-process model in general.

Second, there is little evidence for the efference copy hypothesis of the IOVP effect. The predicted U-shaped function of the w_E parameter was not found in Figure 3 (row 2). With the exception of the far right edge of long words in the *+regressions*, the w_E parameter does not vary systematically with landing position. It should be added that this was not a consequence of fixing the mean and standard deviation of the *E* component. It is obvious from Figure 2 and supplemental materials that the most prominent change across landing positions does not occur at the left edge of the fixation duration distribution; rather it has to do with the shape and location of the peak of the distribution, somewhere between 130-190msec.

Findings from this study strongly support a visually guided strategy in response to unfavorable landing positions. The mean of the *C* component largely falls within the range of 140 and 190msec, which is consistent with the notion that corrective saccades are triggered by the retinal image of the eccentric location. Furthermore, the weight of the *C* component shows a systematic U-shaped relation with the landing position. The timing and function of the *C* component suggests that most corrective eye movements are triggered by the retinal image of the landing position.

It also appears that the *C* component is not exclusively responsive to eccentric landing positions. In fact, as shown in Figure 3 (row 3, *+forward*), w_C is higher at the OVP for short words (e.g., 3 or 4 letters) than at the edges of long words. The fact that the μ_C parameter does not differ systematically between short and long words suggests a single mechanism underlying both cases. It may be more profitable to think of C as a "fast track" response, i.e., a mechanism that triggers saccades faster than normal reading and engaged whenever it is advantageous to move the eyes sooner.

Study 2. The English Story Reading Corpus

The purpose of study 2 is to replicate findings from the Dundee Corpus using a different data set. The *English Story Reading Study* data are part of a cross-linguistic database of reading eye movements (Feng, 2009); only the English data are used here.

Method

The Corpus. Participants were 25 native American English speaking undergraduate students with normal uncorrected or corrected vision. They were asked to read two short novels for comprehension (Feng, 2009). There were approximately 7,500 word tokens, displayed in more than 150 pages. They were asked to answer four comprehension questions after each story. The order of stories was randomized.

Materials were shown on a ViewSonic PF790 CRT monitor running at a refresh rate of 100Hz. Eye-movements were recorded with an EyeLink II eye tracking system (http://www.eyelinkinfo.com), a head-mounted infrared system with a 500Hz sampling rate and a typical accuracy (measured by repeated calibrations) of 0.5 visual degrees. A chin rest was used in conjunction with the built-in head movement compensation mechanism to minimize head movements. A 9-point calibration was done at the beginning of each story and repeated as necessary during the experiment. Eye movement data were parsed into fixations and saccades using the built-in algorithm: saccade detection was based on a an acceleration threshold of $9500°/s^2$ and a velocity threshold of 30°/s. Data from the right eye were used whenever available.

Data coding and selection. The dataset consists of over 168,000 eye movements. Fixations were excluded from analyses if (a) they were not the first fixation on a word or (b) the fixated word was longer than 8 letters or shorter than 3 letters. As in study 1, there were not enough fixations on words longer than 9 letters to accurately estimate model parameters. In addition, study 2 also included a gaze-contingent display change manipulation (to be discussed in study 3) that occurred every 8 to 10 eye movements. Fixations following the display changes were excluded from the present analyses. Approximately 4-12% fixations were excluded for these reasons for each reader.

The coding for landing position differs slightly from that in the Dundee corpus: instead of starting from letter position 0, the current coding starts with 1 for the first letter.

Modeling. The mixture model is identical to that in study 1, except for values of the fixed parameters of the N component. Following the same heuristics, the mean was set to 200msec and the standard deviation was 70msec for the Story Reading corpus. All other aspects of the modeling were identical to those in study 1.

Results

The IOVP effect. As shown in Figure 4, there is an overall IOVP effect for words 4 letters or longer (left panel). The quadratic term of one-way ANOVA was significant for 4-letter words, $F(1,17822)=6.628,\ p=.010$, for 5-letter words, $F(1,14839)=28.643,\ p<.001$, for 6-letter words, $F(1,11677)=54.124,\ p<.001$, for 7-letter words, $F(1,9551)=70.202,\ p<.001$, and for 8-letter words, $F(1,6889)=91.064,\ p<.001$. Unlike the Dundee data, the IOVP effect is asymmetric, i.e., more pronounced on the right side of long words.

There are both similarities and differences between the two corpora when data are broken down by the types of subsequent fixations. The mean duration (Figure 4, top panels) for the *+forward* fixations shows an attenuated IOVP effect. The mean for *+refixations*, however, shows striking differences from the counterpart in Figure 1: it peaks at about 2 letters to the left of the word center, and starts a rapid decline of approximately 60msec over 6 letter positions. This, coupled with the elevated rate of refixations, contributes to the asymmetry of the IOVP effect. The mean for *+regressions*, while showing signs of the IOVP effect, fluctuates more due to smaller sample sizes.

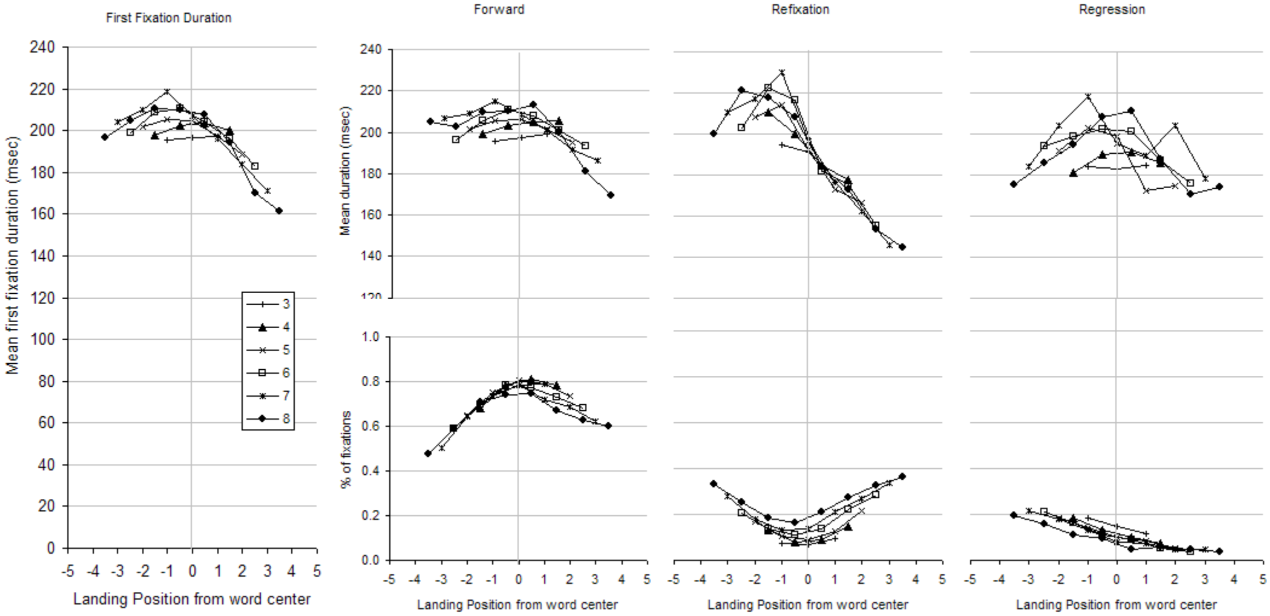

Figure 4. The IOVP effect in the Story Reading Study Corpus (left panel), and its breakdown by the type of subsequent saccades. The top panels on the right show the mean duration of +forward, +refixation, and +regression fixations. The corresponding bottom panels show the proportion of the said fixations at each landing position.

Patterns of the proportions of the three types of fixations (bottom panels) are similar to that in Figure 1, except that landing positions to the right of the OVP show an increased probability of refixation; the rate of refixations in Figure 4 shows the classic U-shaped curve, centered slightly to the left of the word center. Conversely, the rate of forward saccades shows an (asymmetric) inverted-U shape.

Goodness-of-fit of mixture models. Like in study 1, the 3-parameter mixture model succeeded in fitting the 99 empirical distributions (see supplemental materials for distribution functions). For the purpose of the present study, the mixture model captures major features of empirical distributions without over-fitting peculiarities of each observed sample. Chi-square statistics are shown on individual distribution plots, though they have limited utility in the current study.

The μ_C parameter. The first row of Figure 5 shows the estimated values of the mean parameter of the *C* component. For the *+forward* fixations, a linear regression shows that μ_C decreases with landing position at the rate of -4.0msec/letter, *t(30)=5.169, p<.001*, but it is not a function of word length, *t(30)=0.685, p=.516*. For the *+refixations*, μ_C is a function of both landing position and word length. The unstandardized regression coefficient for landing position is -9.7msec/letter, *t(30)=9.660, p<.001* and the coefficient for word length is –3.3msec/letter, *t(30)=2.974, p=.006*. Finally, there was no effect of landing position or word length for *+regressions*, *t<1* in both cases. Thus, for the majority of fixations (*+forward* and *+refixation*) the mean of the *C* component becomes substantially shorter at the right edge of the word, up to 70msec compared to the beginning of the word.

The w_E parameter. The estimated proportion of the *E* component is shown in Figure 5, row 2. The w_E parameter remains lower in this corpus compared to that in the Dundee corpus, reflecting the fact that empirical distributions from the Story Reading corpus have smaller “bumps” of brief fixations. Linear regressions found no effect of landing position, for *+forward* fixations, *t(30)=1.078, p=.286*, and *t<1* for *+refixations* and *+regressions*. Like in Figure 3, there is a slight elevation of refixation rate near the OVP, particularly for short words. This most likely reflects the difficulty in discriminating “real” saccades from microsaccades (e.g., Engbert & Kliegl, 2003; Inhoff & Radach, 1998) and system noises.

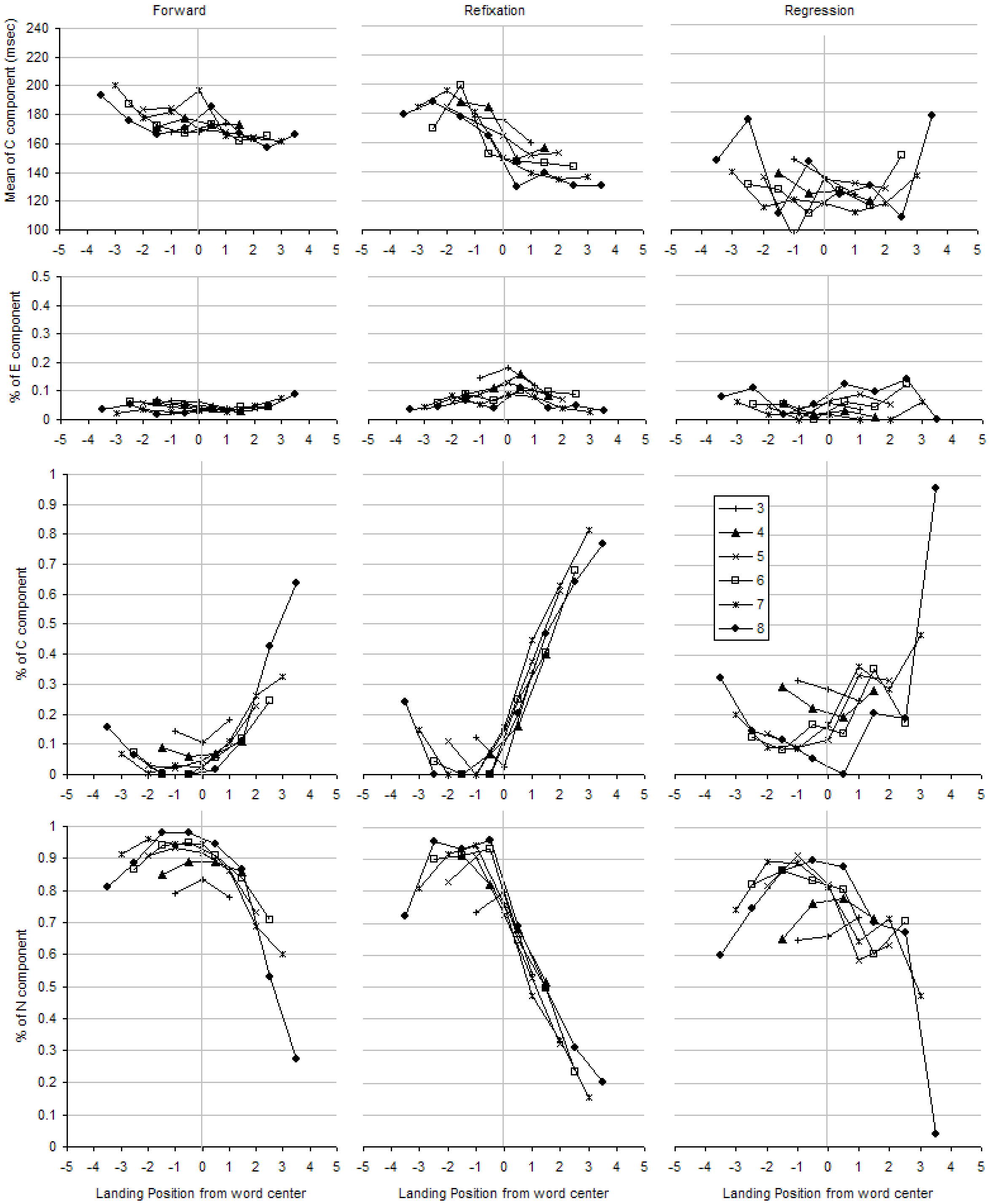

Figure 5. *Estimates of* μ_C *(1st row),* w_E *(2nd row),* w_C*, (3rd row), and* w_N *(4th row) parameters based on the Story Reading corpus.*

The w_C and w_N parameters. The w_C (Figure 5, row 3) and w_N (row 4) parameters virtually mirrors each other because w_E shows little systematic relations with landing positions. The w_C parameter shows a U-shaped relation with landing position in all three types of subsequent saccade, and the function is strongly asymmetrical: the probability of making *C*-type fixations is much higher in the right side of the word than the left side. This is particularly prominent among the *+refixations*, where the 70 percentage increase in the w_C combines with the rapid decrease of μ_C is responsible for the strong IOVP effect on the right side of the word. A similar trend is seen among *+forward* and *+regression* fixations, though estimates of the *+regressions* are noisier due to smaller sample sizes.

Discussion

Study 2 replicated major findings in study 1 with an independent eye movement corpus. The Story Reading corpus shows a strong IOVP effect. The 3-parameter mixture model offers satisfactory fit to 99 empirical distributions, and its parameters show important similarities with those reported in study 1.

There is, again, no evidence for the efference copy hypothesis. The proportion of the *E* component does not vary systematically with the landing position. Like in study 1, the IOVP effect is driven by parameters of the *C* component. Its timing (mostly between 120-190msec) and its U-shaped relation with landing position hints at an error detection mechanism based on retinal visual input.

Comparing readers' oculomotor strategies from the two corpora reveals interesting similarities and differences, and it appears that readers responded differently to the left and right halves of the word. On the left side of the word, the mean fixation duration was comparable between the two databases, so are the probabilities of *+forward* fixations, *+refixations,* and *+regressions*. In both corpora, the left half of the IOVP curve is driven by a decrease of *+forward* fixations and an increase of *+refixations* and *+regressions* at eccentric locations; the latter two categories contain higher proportions of *C*-type fixations at eccentric positions, which yields smaller mean fixation duration compared to that at the OVP.

In contrast, readers show very different strategies on the right half of the word. For the Dundee readers, fixations landed on the right edge of a word did not trigger corrective saccades any more than those landed on the word center. Instead, there was a substantial increase in the proportion of *C*-type fixations in *+forward* and *+refixation* fixations, which drives down the mean fixation duration. In the Story Reading corpus, however, a number of factors worked together to ensue a dramatic IOVP effect on the right side of the words. This involved an increase of the rate of refixations and a drastic change in the distributional parameters – decreasing μ_C (particularly for *+refixations*) and a rapid rise of w_C on the right side of the word. It looks as if readers in the Story Reading study were more invested in correcting unfavorable landing positions – particularly those near the end of words – compared to Dundee readers. Taken together, readers seem to engage in different corrective strategies when the landing position is at the beginning versus the end of a word. The asymmetry will be revisited in General Discussion.

Study 3: The Screen-shift Study

Studies 1 and 2 cast some light on the timing of the corrective mechanism; study 3 investigates what triggers the corrective process. Here we consider two separate issues – (a) whether corrective saccades occur when fixations missed their intended targets or when they landed on unfavorable locations, and (b) whether such corrections are based on the efference copy or on the retinal input. The mislocated fixations hypothesis (Engbert, et al., 2005; Nuthmann, et al., 2005; Nuthmann, et al., 2007) stipulates that corrective saccades occur when fixations miss their targets and the detection is based on the internal efference copy mechanism without the involvement of the visual input. The refixation mechanism in the E-Z Reader model (Pollatsek, et al., 2006) concerns fixations at eccentric landing positions and hence requires the retinal input. The approach here is to try to decouple the two issues.

In naturalistic reading it is impossible to tell which saccade has missed its target. Study 3 artificially causes mislocated fixations using a gaze-contingent display change technique, whereby the text on the screen is shifted left or right during selected saccades (Inhoff, Weger, & Radach, 2005; Nuthmann, 2006; O'Regan, 1981) (see Figure 6). As a result, the eyes will land a few letters off the intended target. Sometimes this results in eccentric landing positions, and other times the eyes ends up on a different word. Because the display changes occur during the saccadic suppression, the shift itself is not perceived (Matin, 1974; McConkie & Loschky, 2002; Rayner, 1998; Wolverton & Zola, 1983). Mislocated fixations are ubiquitous in normal reading and may account for 10-30% of fixations (Engbert & Nuthmann, 2008). The screen shifts simply add to the number of mislocations. Because screen shifts occur only among approximately 10% of saccades, the ecological impact is minimized.

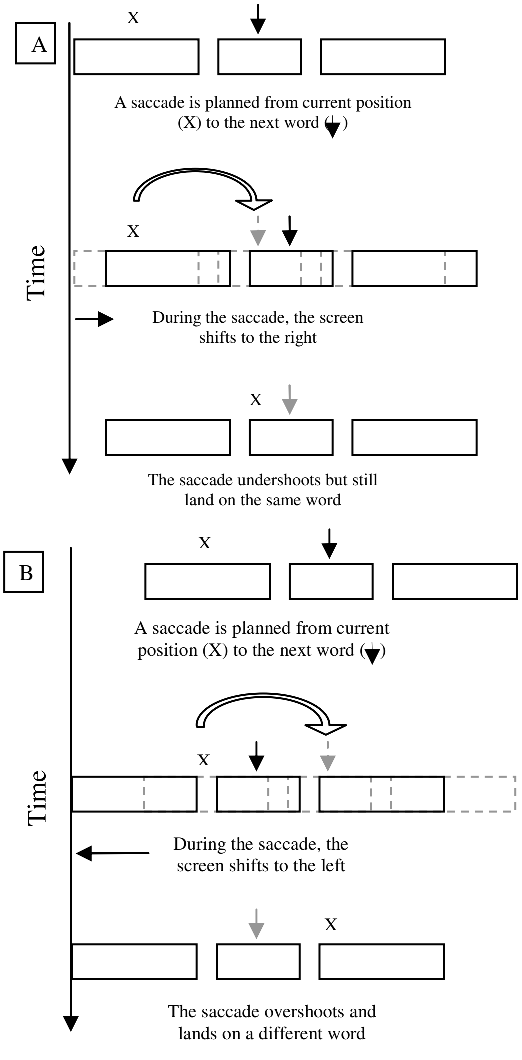

Figure 6. Illustration of the gaze-contingent screen shift paradigm. Panel A shows a rightward screen-shift where the eyes undershoot but land on the same word. Panel B illustrates a case in which a leftward screen shift causes the eyes to overshoot and land on a different word. This creates a mislocated fixation.

Two hypotheses are tested here. The first question is whether corrective saccades are initiated because the eyes have landed on an unfavorable position or on a wrong word. If mislocated fixations routinely trigger corrective saccades, there should be an increase of brief fixations when the eyes land on a wrong word due to screen shifts, assuming mislocated fixations are detected based on the retinal input. Obviously, this is not a direct test of the original “mislocated fixations hypothesis” (Engbert, et al., 2005; Nuthmann, et al., 2005; Nuthmann, et al., 2007), which assumes that saccades are triggered by the efference copy mechanism. Because the efference copy is made prior to the saccade (Bridgeman, 1995) and because visual perception is severely suppressed during saccades (Matin, 1974), the gaze-contingent screen shift manipulation cannot influence the efference copy mechanism. However, there are reasons to question the role of the efference copy in triggering corrective saccades. Conceptually, the efference copy of the oculomotor plan is made *before* the saccade occurs. The detection of mislocated fixation requires accurate real-time information about subsequent oculomotor errors, in addition to the intended target. It is not clear whether such information is available during saccades, and whether it is reliable enough to be the basis for corrective actions. Studies 1 and 2 also found little support for the efference copy hypothesis. Thus, instead of the efference copy mechanism, this study tests an *alternative* mislocated fixations hypothesis, namely whether the mislocated fixations are detected visually.

Second, if corrective saccades are triggered by the internal efference copy mechanism without the visual input, there should observe larger IOVP effect in the *pre-screen-shift* metric. On the other hand, if saccadic errors are detected based on the retinal input, then a stronger pattern of the IOVP effect should be seen in the *post-screen-shift* metric. This prediction applies regardless of whether the corrections are triggered by unfavorable landing positions or by missing intended words.

Method

The screen shift manipulation was part of study 2; information about the participants and materials can be found in the corresponding Method section. Here we concentrate on the screen shift paradigm.

The screen shift paradigm. Participants were instructed to read the stories normally for comprehension and were not warned about the screen shifts. There were no screen shifts during the first 5 pages of each story. After these, at the onset of every 8th-12th saccade (randomized), texts on the screen were shifted to the left or the right by 1-3 character spaces (also randomized); the size of the shifts was comparable to naturally occurring oculomotor noises (McConkie, et al., 1988). Figure 6 illustrates two examples of screen shifts. Panel A shows (top to bottom) three snapshots before, during, and after a saccade. During the preceding fixation, a saccade is programmed to the center of the next word, marked by the arrow. As the saccade starts, the screen is shifted to the right by a small amount. Consequently the eyes undershoot the intended target (operationalized as the landing position in the pre-shift metric), but in this case they still land on the same word. Panel B shows a case in which a large leftward screen shift causes the eyes to miss the target word altogether. The eyes, overshooting the target, land on the beginning of the next word. By comparing the landing position in the *pre-shift* and *post-shift* metrics, artificially created mislocated fixations such as this can be identified.

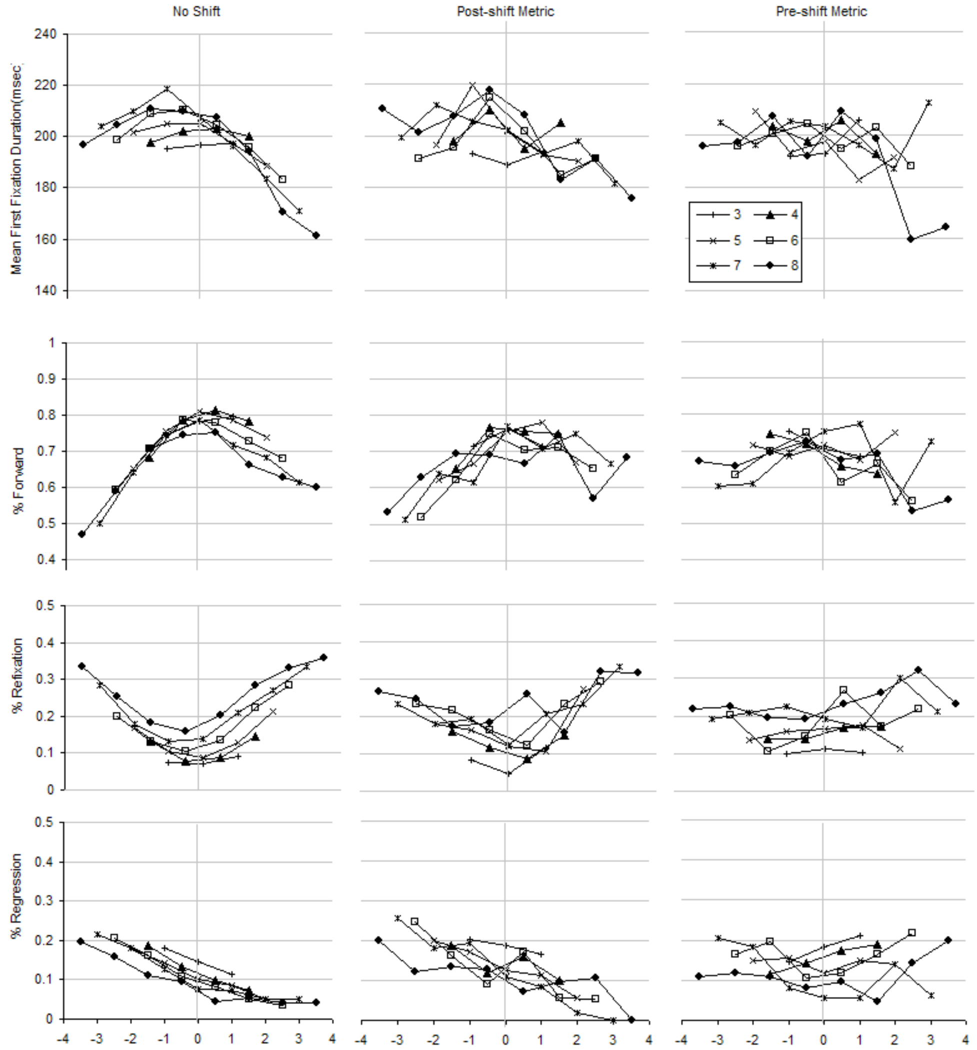

Figure 7. Mean first fixation duration and probabilities of +forward, +refixation, and +regression fixations without screen shifts (left column) or with screen shifts. Fixations after screen shifts are plotted either in the post-shift metric (middle column) or the pre-shift metric (right column).

Display changes that occurred during a saccade or within a few milliseconds after the onset of the subsequent fixation are imperceptible because visual processing is suppressed (Matin, 1974; Rayner, 1998; Wolverton & Zola, 1983). To achieve fast display changes, a fast monitor with a refresh rate of 100Hz was used. Data filters on the eye tracker were also turned off to reduce communication delays. A custom designed algorithm detects the onset of saccades using a velocity-based criterion (30°/s). The typical delay for saccade detection was 8msec, and the average delay of screen refresh was approximately 5msec (worst case 10msec). Most screen shifts (94.5%) were completed within 8msec of the onset of the subsequent fixation and were not perceived by readers (McConkie & Loschky, 2002). The screen shift was cancelled if the eyes were close to the beginning or the end of a line. This was a precautious measure to prevent the readers from detecting screen shifts by using text boundaries as a reference. In post-experiment debriefings the majority of participants were unaware of any screen changes, and those who reported occasional flicking of the screen rated them as infrequent, even though they occurred every a few seconds.

Results

Pre- and post-shift metrics. Figure 7 shows the mean first fixation duration and the probability of *+forward*, *+refixation*, and *+regression* fixations as a function of landing position and word length. The left column depicts fixations with no screen shifts, same as in Figure 4. The middle column shows fixations after the screen shift manipulations, in the *post-shift* metric (i.e., actual landing positions). The right column summarizes the same fixations after screen shifts, but in the *pre-shift* metric (i.e., *intended* landing position before the screen shift). If corrective eye movements are planned using the efference copy mechanism, we should see an IOVP effect based on the *pre-shift* metric; on the other hand, if corrections are triggered by the retinal input, then an IOVP should be demonstrated in the *post-shift* metric.

Compared to the left column, the post-shift metric shows a clear IOVP effect, whereas the pre-shift metric produces an ambiguous pattern. To quantify similarities between conditions, correlation coefficients were calculated based on the 33 combinations of landing positions and word lengths. With regard to the mean fixation duration, the correlation between the “no shift” and “post-shift” conditions was r=0.667, $t(31)=4.985$, $p<.001$, and it was r=0.210, $t(31)=1.196$, $p=.2406$, between the “no shift” and the “pre-shift”. For saccade probabilities, the correlation coefficients between the “no shift’ and “post-shift” conditions were 0.800, 0.868, and 0.870 for *+forward*, *+refixation*, and *+regression* fixations, respectively. They are highly significant, $t(31)=7.4004$, $p<0.001$, $t(31)=9.7535$, $p<0.001$, and $t(31)=9.8427$, $p<0.001$, respectively. In comparison, the correlations between the “pre-shift” and “no shift” probabilities were lower at 0.391, 0.663, and 0.215 for *+forward*, *+refixation*, and *+regression* fixations, respectively. The first two correlation coefficients are statistically significant, $t(31)=2.3676$, $p=0.0243$ and $t(31)=4.9246$, $p<0.001$ but the correlation for the *+regression* fixations is not significant, $t(31)=1.2266$, $p=0.2292$. Some significant correlations between “no shift” and “pre-shift” probabilities are expected, because the screen was shifted only by 1 to 3-letter, which had only limited impacts on the landing position distribution of long words. Overall Figure 7 strongly suggests that the oculomotor decision took into account visual input obtained during the on-going fixation.

Mislocated fixations. This analysis addresses the question of whether corrective saccades are triggered by mislocated fixations or eccentricity. Figure 8 compares the proportions of *+forward*, *+refixation*, and *+regression* fixations in the “no shift” condition and fixations that overshot (squares) or undershot (triangles) intended words due to gaze-contingent screen shifts. Because screen shifts were limited to up to 3 letters, most overshooting fixations landed on the first two letters of the subsequent word, and they are compared to the “no shift” probabilities at the word initial positions of the corresponding word length. Similarly, most undershooting fixations ended up on the last two letters of the previous word. They are compared to the word-end positions of the “no shift” data. There are altogether 101,136 no-shift fixations, 1,295 left-shift (overshooting) fixations, and 980 right-shift (undershooting) fixations. The error bars indicates standard errors.

Figure 8 shows that when the eyes undershot a word due to a rightward screen shift, the probabilities of making subsequent forward, refixation, and regressive saccades are very similar to those found in the end of words in the “no shift” condition. In other words, no special corrective responses are observed for undershooting mislocated fixations. The picture is somewhat different for overshooting fixations, which were caused by leftward screen shifts and landed primarily on the first two letters of the “wrong” word. Whereas the rate of refixations does not appear to differ from the “no shift” condition, there are significant increases in the rate of regressions and corresponding drops in forward saccades. Although this is consistent with the prediction of the mislocated fixations hypothesis, it only affected approximately 10% of mislocated fixations. The majority of mislocated fixations in the overshooting case followed the standard oculomotor responses.

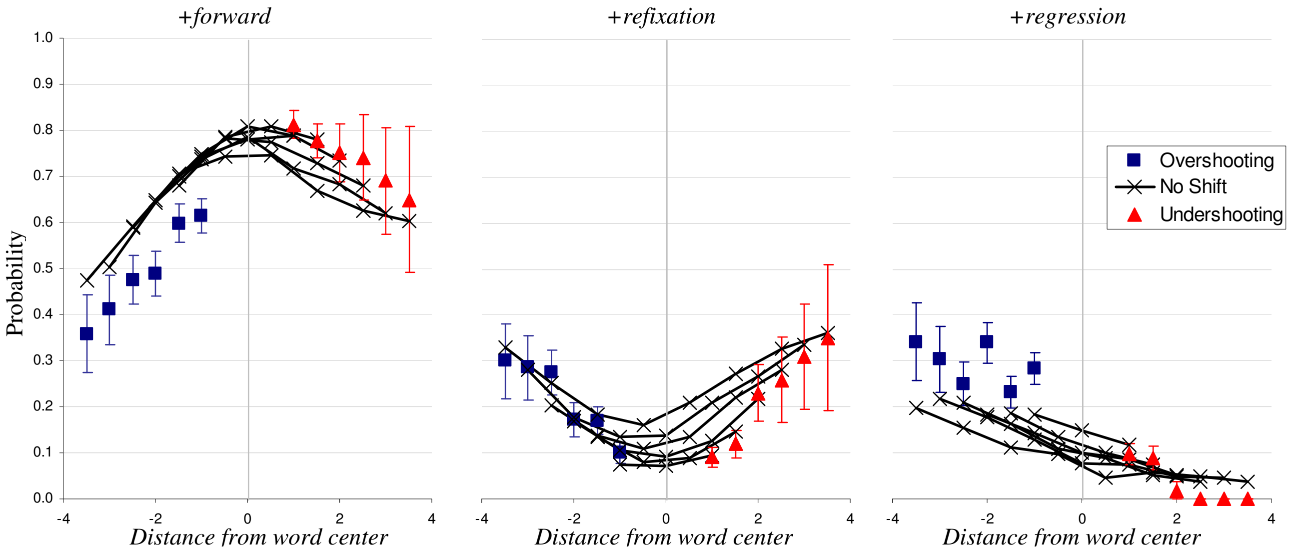

Figure 8. Probabilities of +forward, +refixation, and +regression fixations for mislocated fixations and fixations not affected by screen shifts. Different lines and markers represent different word lengths.

Distribution of fixation duration. Distribution functions of first fixation durations for “no shift”, “overshooting”, and “undershooting” fixations are shown in Figure 9. Due to the limited numbers of screen shifts, each distribution includes fixations from all word lengths. In this study mislocated fixations usually land on the first two letters (overshooting, row 2) or the last two letters (undershooting, row 4) of words. For comparison, “no shift” distributions are also restricted to the first two landing positions (row 1) or the final two letters (row 3). The same 3-parameter mixture model as in study 2 was fitted to the nine distributions.

In the case of overshooting fixations, where the eyes land on a new word, the distribution of first fixation duration differs little from that of normal reading fixations landing on the same positions. In the case of undershooting fixations, where often the eyes end up on the same word due to the screen shift, there appears to be an increase of the *C* component among *+forward* and *+refixation* fixations, compared to fixations not preceded by screen shifts.

This analysis addresses an additional concern, namely gaze-contingent screen shifts could have created flicking or other artifacts that would interfere with normal oculomotor programming. This is not the case: Figure 9 shows no evidence of excessive early saccades or long pauses.

Discussion

Using the gaze-contingent screen shift paradigm, study 3 provides further evidence in favor of a visually-guided corrective process. Fixations after screen shifts show much more similarities to the no-shift condition when data are summarized using the actual landing position, i.e., the *post-shift* metric. The similarity is substantially attenuated when plotted using the *pre-shift* metric. If a wider range of screen shifts were used, the similarity would likely disappear altogether under the *pre-shift* metric. With regard to the time course, mislocated fixations do not trigger brief fixations in the range predicted by the efference copy hypothesis.

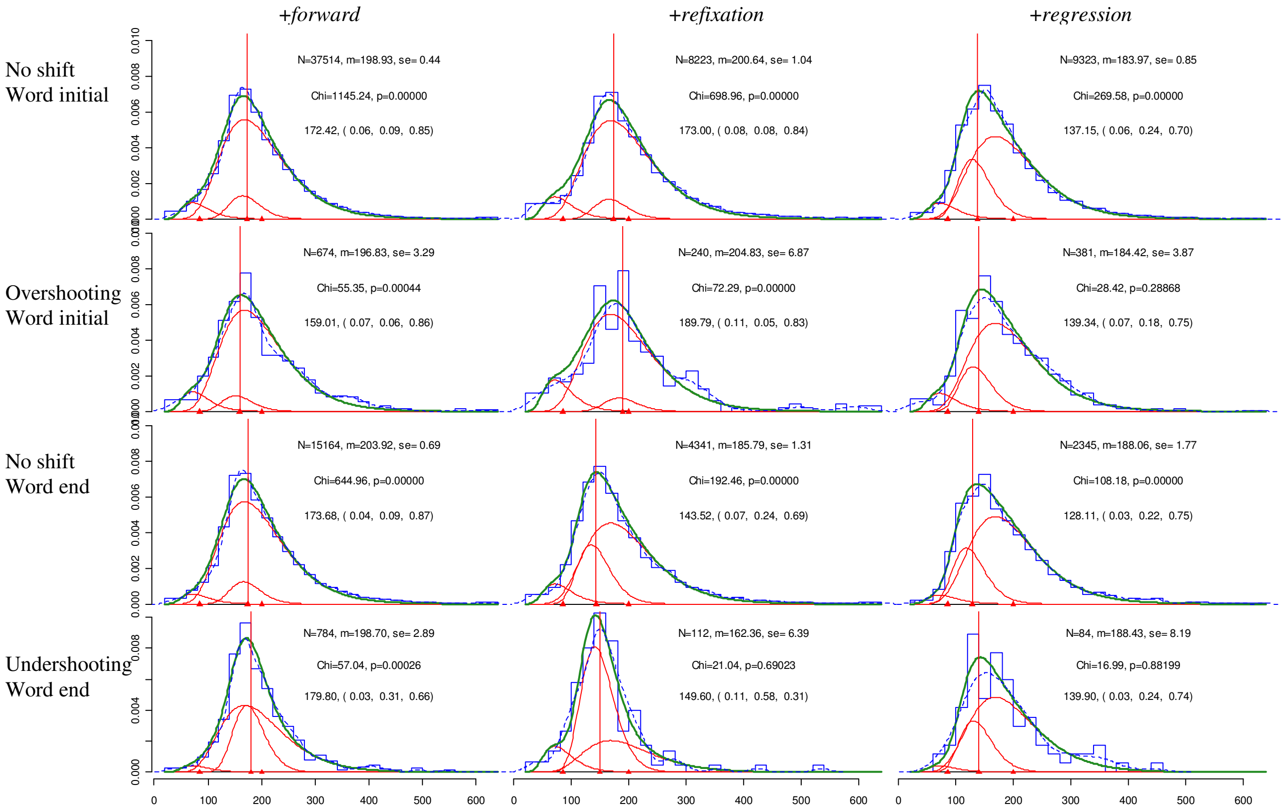

Figure 9. First fixation duration distribution by the type of subsequent saccades, landing position (word initial vs. word end), and whether the fixation was mislocated due to screen shifts. The sample size (N), mean (m), and standard error (se) are shown for each distribution. The second line shows the Chi-square statistic and the p-value. The third line shows the mean of the E component (in msec) and in the parentheses, relative weights for each component.

Are corrective eye movements triggered by mislocated fixations? The answer is less clear cut. When the eyes overshoot due to screen shifts, there is little change in the fixation duration distribution, which offers no support for the *modified* mislocated fixations hypothesis. A noticeable increase in the rate of regressions is observed, suggesting that readers detected the mislocation and made effort to go back to the original target. This corrective behavior, however, is not predicted by the SWIFT model (Engbert, et al., 2005), and Figure 9 shows no evidence that it is associated with brief fixations. It is likely caused by a different – probably cognitive – process that is distinct from the hypothesized mechanism associated with mislocated fixations. Undershooting fixations, in comparison, show no change in saccade directions but an increase in the *C* component in their duration, which is consistent with the *modified* mislocated fixations hypothesis.

It is unclear why the effect of mislocated fixations is inconsistent and asymmetric with regard to landing positions. On the other hand, there is overwhelming evidence that the actual landing position strongly determine readers' eye movement strategies, regardless of whether the eyes have missed the target word. Data from this study suggest that although mislocated fixations may play some role in triggering corrective saccades, it is unlikely to be the primary factor.

It is always a concern in any gaze-contingent paradigm that results may be contaminated by flicking and artifacts. Cautions have been taken in the design and analyses of the experiment to identify and minimize such risks. In addition to using a fast eye tracking system and a high refresh rate monitor, the number of screen shifts was kept low to minimize potential interferences with normal reading, and screen shifts were cancelled near the beginning or end of a line so that readers could not use the monitor outline as a visual reference. Off-line analyses showed no detectable differences in the distributions of fixations with and without screen shifts. In addition to Figure 8, which compared saccade probabilities between mislocated fixations and “no shift” fixations, a similar analysis was also conducted on post-screen-shift fixations that landed on the same word. The probabilities of making forward, refixative, and regressive saccades thereafter are no different from those of “no shift” fixations at the same landing positions; the result is not presented here as it is consistent with the message in Figures 8 and 9.

General Discussion

The IOVP effect is a reflection of sophisticated changes in oculomotor responses to unfavorable landing positions. This paper introduces a distributional model that goes beyond the mean fixation duration and tests critical predictions by current theories of reading eye movements. Here I will recap main findings from the three studies, and discuss their implications to reading eye movement theories and potential methodological issues.

Underlying the IOVP effect

Evidence for a corrective mechanism. Several theories (Nuthmann, et al., 2005; Reichle, et al., 2006) hypothesized that the IOVP effect is caused by a mechanism that terminate fixations earlier at unfavorable landing positions. Evidence for the corrective mechanism comes from computer simulation (Engbert, et al., 2005; Pollatsek, et al., 2006) and analyses of landing position distributions (Nuthmann, et al., 2005; Nuthmann, et al., 2007). In this study the dual-process model is tested using a mixture model that incorporates distributional components for normal reading fixations (the *N* component), the corrective component (the *C* component), as well as a component for the very brief fixations (the *E* component). The simple 3-parameter model successfully captured the essence of over 200 diverse empirical histograms. Moreover, its parameters – particularly the mean and weight of the *C* component – show systematic relations with landing positions that are consistent with theoretical predictions. The mixture model provides strong support for a corrective mechanism, which varies in propensity and timing with landing position and causes the IOVP effect. This, of course, does not imply that single-process models cannot account for the data (see Van Zandt & Ratcliff, 1995); I will revisit this issue later.

Efference copy in reading. Data from the present study question the role of the efference copy in triggering corrective saccades. Whether or not one agrees with the mixture models, it is evident from Figure 1 and supplemental materials that systematic changes in the distribution function occurs between approximately 120 and 200msec.

The timing of this effect is consistent with that of visually based saccades. For example the typical saccadic response time of pro-saccades in the gap condition is within this time window (Klein & Foerster, 2001). A recent study looking at corrective saccades in a double-step paradigm (Munuera, Morel, Duhamel, & Deneve, 2009) estimated that the mean latency for visually based corrective saccades was approximately 120-140msec, depending on the size of the saccade. Evidence suggests that the retinal input has enough time to influence C-type eye movements.

According to models of mislocated fixations (Engbert, et al., 2005; Nuthmann, et al., 2005; Nuthmann, et al., 2007), the efference-copy-based corrective saccade latency (τ_c) is 125 or 128msec. The number seems high, given that the efferent copy mechanism does not involve the 50-90msec eye-brain lag (e.g., Pollatsek, et al., 2006; Reichle, et al., 2006; Sereno & Rayner, 2003). If we subtract the eye-brain lag from the timing of visually based corrective saccades, one would expect the latency of efference-copy-triggered saccades to be in the range of the E-component. No systematic change in the E component was observed across landing positions.

Besides empirical evidence, there are theoretical reasons to doubt the involvement of the efference copy mechanism in corrective saccades in reading. The efference copy of a motor plan is generated prior to the saccade, and contains no information about the motor error that is going to occur, nor is it updated during the saccade (Bridgeman, 1995). If, for example, the motor command is “go to the center of the next word”, nothing will tell the eye (or the brain) that the saccade is going to miss the target word, by how far, or in which direction. It is unclear how the efference copy mechanism can be used for detecting oculomotor errors. Furthermore, in order to correct only mislocated fixations, the mechanism should respond to between-word oculomotor errors but not within-word errors of the same magnitude; this seems to require more than a motor plan. Third, the reference copy is most useful when the background is uniform; with structural background (e.g., natural scenes), retinal input is preferred (Bridgeman, 1995). Bridgement (2007) further suggests that instead of using the efference copy to keep track of the visual scene across saccades, we perform a fast and limited (<50msec and within a few degrees) visual search in order to establish a continuity across saccades. Errors within this window will be ignored. Reading, as it happens, is based on structured visual input (print texts) and most saccades (and thus saccadic errors) are small. By implication the detection of motor errors is likely to be based on visual input, not the efference copy.

In short, as a prediction of where the eyes *should* be, the reference copy of a motor plan contains no information that will allow the detection of mislocated fixations prior to the onset of the fixation. It is more likely to be based on comparisons of some level of visual representations across saccades.

On mislocated fixations. There is little doubt that mislocated fixations exist (McConkie, et al., 1988; Nuthmann, et al., 2005; Nuthmann, et al., 2007). It is debatable, however, whether they are obligatorily corrected or treated like other fixations at the same landing positions. Costs are inevitable with corrective eye movements, the least of which is the time wasted on the "wrong" word. It seems reasonable to expect such costs to be outweighed, to at least balanced, by some processing benefits. But the economics of the mislocated fixation hypothesis is questionable.

First, if the target of the next saccade is selected probabilistically, as the SWIFT model suggests (Engbert, et al., 2005), there is a non-zero probability that the "accidental" target word would have been chosen as the actual target anyways. In other words, mislocated fixations may be non-consequential in a parallel, stochastic model such as SWIFT. It is not obvious what the benefit is to correct them.

Second, one way to justify the economics is to lower the behavioral cost – the efference copy hypothesis is appealing in this regard because it promises a fast corrective process. The last section outlined reasons to doubt the involvement of the efference copy in identifying mislocated fixations. If the conclusion is true, a visually based detection is the only option.

However, if the detection of mislocated fixations is based on the retinal input, there is even less incentive to correct them. The visual identification of a mislocated fixation will require comparing representations of words across saccades, and possibly even word identification. After this level of processing the cost seems too high to abandon the current fixation. Comparatively, recognizing an unfavorable landing position requires only low-level visual information and may be done quickly. This suggests that mislocated fixations, which are themselves usually at unfavorable landing positions, may be dealt with the same mechanism that handles other eccentric fixations.

Asymmetry. No theory has explicitly predicted an asymmetry in the oculomotor response to unfavorable landing positions. Yet data show repeatedly that readers respond differently depending on whether their eyes land on the left or the right side of words. In study 1, eccentric landing position on the left side of the word triggered more refixations but not on the right side. In study 2, the IOVP effect is much stronger on the right side, driven by an increasing weight and decreasing mean duration of *+refixations*. In study 3, mislocated fixations landed on the end of words (undershooting) do not show any differences in saccadic probabilities compared to no-shift fixations, although those landed on the beginning of words (overshooting) triggered more regressions. None of these asymmetric responses is predicted by current theories. Together they suggest a more prudent response to the first half of words compared to the second half.

Implications to current theories

Results from this paper suggest that corrective saccades are triggered by the visual input obtained since the onset of the fixation, particularly at unfavorable landing positions. In this regard the data are mostly compatible with predictions of the E-Z Reader model (Pollatsek, et al., 2006; Reichle, et al., 2006). Important discrepancies remain, however. For example, the E-Z Reader model specifies that fixations not affected by the automatic refixation mechanism are longer for eccentric landing positions and for longer words (Reichle, et al., 2006); the current model finds a fixed N component sufficient for the distributional modeling. Other issues such as the asymmetry of eye movement responses remain to be investigated.

The notion of a corrective mechanism that triggers saccades earlier than in normal reading is also consistent with the SWIFT model (Engbert, et al., 2005; Richter, Engbert, & Kliegl, 2006), which also assumes that the direction of the corrective saccade is determined by the visual information obtained from the fixation. However, data from this study question the involvement of the efference copy mechanism, an important assumption of the mislocated fixations hypothesis (Nuthmann, et al., 2005; Nuthmann, et al., 2007). An immediate implication to the SWIFT model is that the triggering of corrective saccades should be postponed to accommodate the eye-brain delay. The current study also suggests that alternative mechanisms may be needed in addition to the mislocated fixations in order to account for eye movement responses to oculomotor errors and unfavorable landing positions.

The LATER model has been shown to account for a range of fixation duration distributions in reading and other oculomotor tasks (Carpenter & McDonald, 2007; McDonald, et al., 2005; Reddi, et al., 2003). The reci-normal distribution shares with the lognormal distribution a unimodal hazard function with a slow falling tail (Feng, 2009), which makes it appropriate for modeling the right tail of empirical fixation duration distributions. However, the LATER model often requires a second reci-normal distribution to fit shorter fixations (Carpenter & McDonald, 2007). It remains to be seen if a single-process LATER model is able to account for fixation duration distributions at different landing positions.

More on corrective eye movements

The mixture model presented in this paper is first and foremost a mathematical description of readers' eye movements. Despite its parsimony and success in account for empirical data, the phenomena captured by the model do not fit easily to existing cognitive and neuroscientific theories of reading eye movements. To understand the underlying mechanism that generates the mixed responses to unfavorable viewing positions, it may be profitable to take a functional perspective and examine the role of these corrective eye movements in making reading more effective. To this end several observations can be made:

1). With its smaller mean and standard deviation, primary function of the *C* component is to terminate reading fixations early and consistently, compared to normal reading. It seems to be a general mechanism to speed up eye movements, as it is observed both with short words and at unfavorable landing positions. Meanwhile, in the current model parameters for normal reading fixations did not have to vary with landing position or word length. The mixture model provides an alternative mechanism for optimizing looking time on words, whereby the mean fixation duration is fine-tuned by adjusting the proportion of corrective fixations.

2). Corrective fixations are triggered by the visual input. Its mean parameter, which rarely goes below 130msec, suggests that the decision to move the eyes is made after the visual cortex has started processing the visual input from the retina. Findings from the present study can be explained by low-level visual information – both landing position and word length are reflected in the configuration of letters and spaces. When there are no spaces close to the center of the fovea, i.e., when the landing position is near the OVP, few *C*-type fixations are initiated. It remains unclear whether corrective saccades can be "fast-tracked" by higher-level processes such as lexical processing, sentence processing, or reading strategies.

3). Parameters of the *C* component also depend on the types of subsequent saccades. Both study 1 and study 2 show that μ_C is on average lower for *+refixations* and *+regressions* and longer for *+forward* fixations. This is consistent with empirical findings that fixations are shorter if they are followed by regressions than progressions (e.g., Vitu, McConkie, & Zola, 1998). The proportion of the *C* component varies greatly with the type of subsequent saccade. The connection between *when* to move the eyes and *where* to move the eyes requires further research.

4). Corrective fixations seem to be generated strategically rather than mechanically. For example, word initial positions and word end positions elicit different proportions of *C* components (Figures 3 and 5). Additionally, readers in the two corpora appear to have different oculomotor responses to landing positions – Dundee readers rarely corrected eccentric fixations at the end of words, whereas readers in the Story Reading study made more refixations from the end of words but did so with faster saccadic response time. Nonetheless, in both cases the average fixation duration at eccentric positions near the word end is substantially lower than that at the OVP.

Overall, these eye movement responses can be seen as simple heuristics that serve to optimize oculomotor planning for reading: unfavorable conditions are quickly identified based on low-level perceptual cues, and are dealt with using specialized routines that fast-track oculomotor decisions. As the perception-economy theory (Vitu, et al., 2007) suggests, these strategies emerge in order to make reading more efficient. The particular eye movement strategies readers engage differ from situations to situations, from one language to another, and from beginning to proficient readers (Feng, 2003, 2006a, 2006b, 2008; Feng & Guo, under review). Rather than assuming a monolithic mechanism of reading eye movements, it is profitable to investigate what perceptual, oculomotor, and cognitive faculty readers tap into to develop heuristics that make reading second nature.

On Mixture Modeling

As a new analytical technique, the mixture modeling technique requires more scrutiny. A fundamental question is how much of its result is determined by the empirical data and how much is in the hands of the modeler. The answer is two-fold: (a) distributional models are subject to more constraints than traditional linear models, and (b) steps can be taken to ensure replicability of distributional analyses. Efforts are taken through out this paper to document the rationales behind these decisions. I will discuss some of the potential alternative model strategies below.

Distributional models. Systematic changes in the distribution of fixation duration exist, with or without a mathematical model. The main conclusions of this paper can be "read" directly from the over 200 empirical histograms (see supplemental materials). But instead of – or perhaps in addition to – verbal descriptions such as "the peak of the distribution shifts to the left" or "there is no apparent change in the left tail of the distributions," a mathematical model does a better job in characterizing these distributional changes.

Like any other modeling efforts, distributional models are subject to two competing restrictions – parsimony and the goodness of fit. A model with arbitrary distributions and parameters may fit the data but is unlikely to be parsimonious; an overly restrictive model will fail to capture the data. These competing demands minimize arbitrariness in modeling. For example, any distributional model must capture the initial "bump" of very brief fixations, the steady long tail on the right, and the peak of the distribution that varies in its location and kurtosis. These distributional features cannot be reduced to sample means and variances.

The mixture model. The mixture model is a straightforward extension of theoretical models of reading eye movements (Engbert, et al., 2005; Nuthmann, et al., 2005; Reichle, et al., 2006). The lognormal distribution is one of a minority of theoretical distributions with a hazard function that resembles that of empirical reading fixation duration (Feng, 2006a, 2009). And finally, a 3-component lognormal mixture model has been shown to successfully simulate a diverse set of empirical fixation duration distributions (Feng, 2006a). The contribution of the current model is not so much in expanding prior work, but to restrict the number of free parameters. In doing so, the psychological meaning of model parameters become more apparent.

The mixture mode presented here is the first distributional model of the IOVP effect. There are distributional models of fixation duration based on other architectures (e.g., Carpenter & McDonald, 2007; Feng, 2009; McConkie & Dyre, 2000). It is interesting to see which model provides a more flexible and parsimonious account of reading eye movements. Most likely, though, they will involve at least three free parameters, to account for the initial "bump", the peak, and the long tail in the observed distribution. In this regard, the mixture model has the advantage of offering a straightforward interpretation for the parameters.

Free and fixed parameters. The rationale for restricting the number of free parameters has been articulated before. However, questions may be raised about particular decisions: for example, why was the mean for the *E* or *N* component not a free parameter? The answer has to do with a balance between parsimony and the overall fit of the model. Across landing positions, the largest variation is the location and kurtosis of the peak of the empirical distribution. When the *C* component is fixed, no combinations of *E* and *N* components can satisfactorily capture observed data. If the mean of *C* is free, there is relatively little advantage to allow *N* to vary as a function landing position or word length. No U-shaped relation with landing position is found when the mean and standard deviation of the *E* component were estimated as free parameters. Finally, the present study tries aggressively to keep the number of free parameters minimal in order to compare parameters across conditions. Future research may strike a different balance between the need for parsimony and for goodness-of-fit.

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