SWIFT predictions on standard eye movement effects

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1 Distributions of Fixation Durations and Saccade Lengths

As a first statistical result, we compared the distributions of fixation durations for model simulations to the respective experimental data. Figure S1 shows that the random walk assumptions can explain the variance contained in fixation durations. Also the experimentally observed task differences, i.e., an increase in mean and variance of fixation durations for shuffled text reading, was captured by the shuffled-SWIFT model.

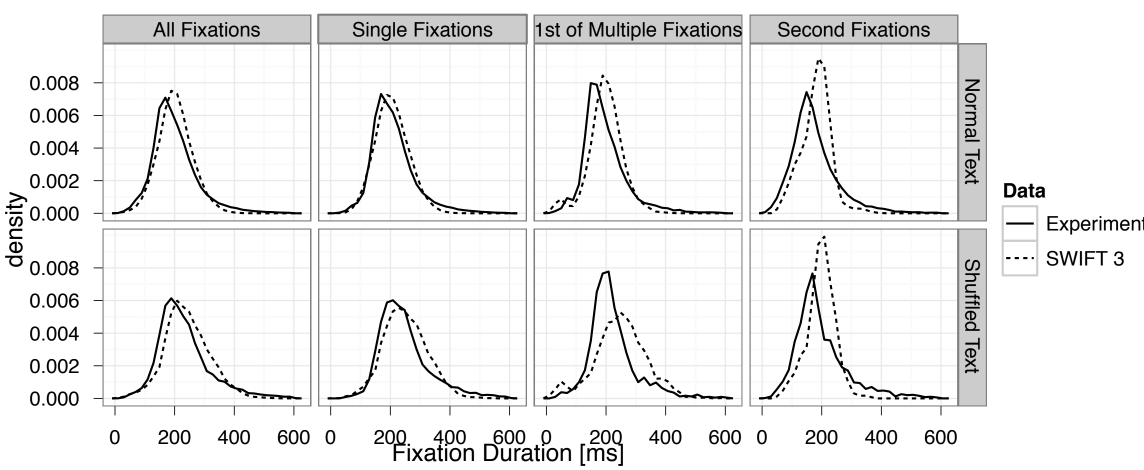

Figure S1

Distributions of fixation durations for experimental data (solid lines) and model simulations (dashed lines) for normal (upper panel) and shuffled (lower panel) text. Fixation duration measures: All valid fixation durations (left panel), single fixation durations (middle left panel), first of multiple fixation durations (middle right panel), second fixation durations (right panel).

Distributions of saccade lengths were well reproduced for reading of normal text, particularly for forward-directed saccades (Figure S2). Note that the SWIFT model produces distributions for forward-directed and regressive saccades based on one single mechanism. Saccade lengths during shuffled text reading were somewhat shorter, which was well reproduced by the shuffled-SWIFT model. The experimentally observed reduction in variance of forward saccades, however, was not evident in the model simulations. Note that the distributions of fixation durations and saccade lengths were not included into the function for optimizing model parameters.

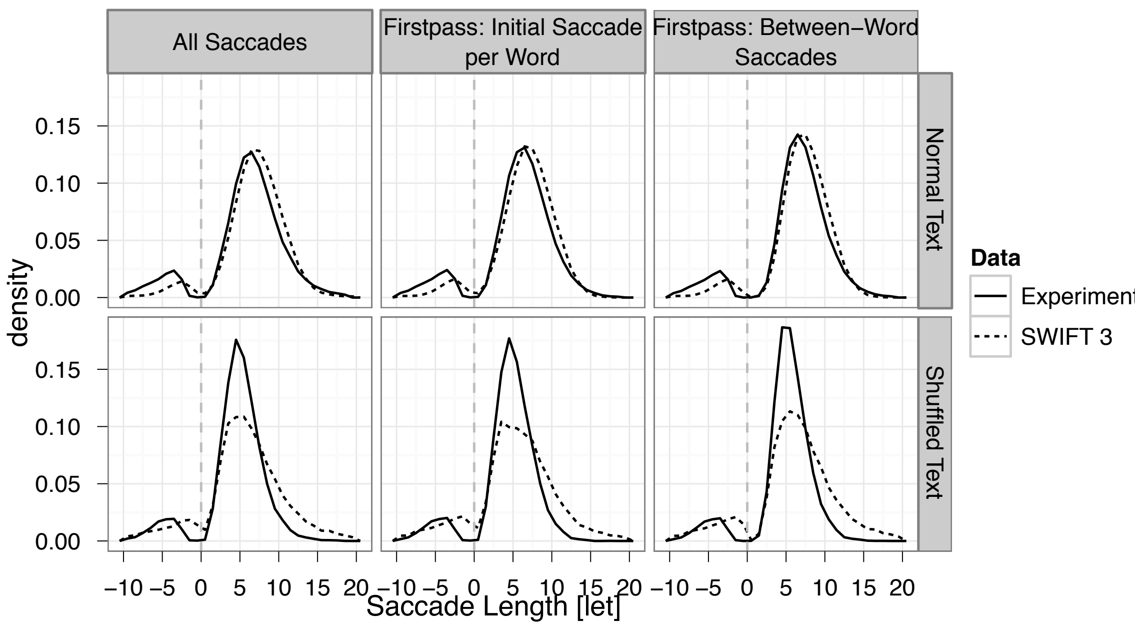

Figure S2

Distributions of saccade lengths for experimental data (solid lines) and model simulations (dashed lines) for normal (upper panel) and shuffled (lower panel) text. Positive values indicate forward-directed saccades, negative values indicate the lengths of regressive saccades. Measures of saccade lengths: All valid saccades (left panel), initial saccade after initially fixating a word in firstpass (middle panel), between-word saccades in firstpass (right panel).

2 Initial Landing Positions

Given a good agreement of distributions of fixation durations, we now investigate basic oculomotor assumptions in the SWIFT model. The landing positions of initial fixations on a word during reading approximately follow Gaussian distributions and exhibit a considerable variance. Important factors influencing the maximum and variance of landing position distributions are the launch site distance and word length (McConkie et al., 1988).

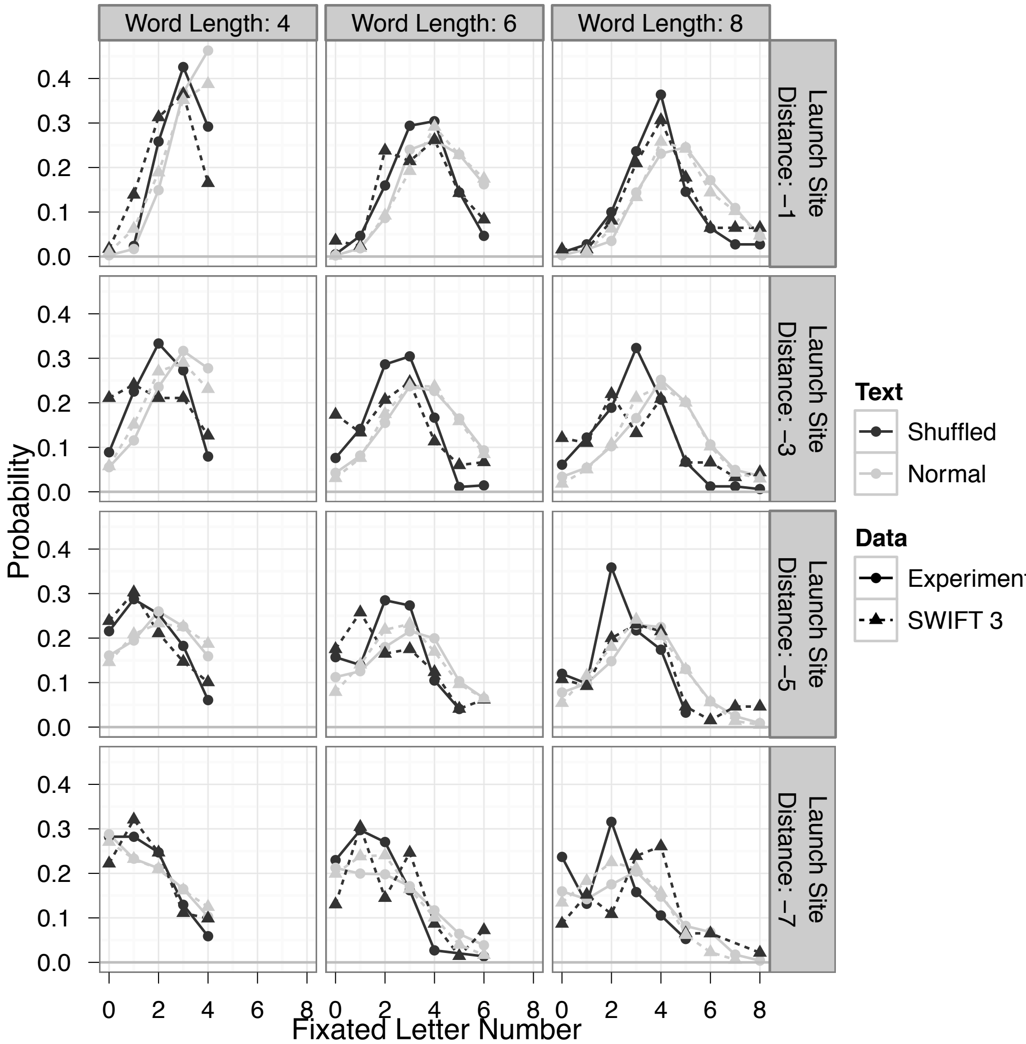

Figure S3

Distributions of initial landing positions by word length and launch site distance. The columns of panels show distributions for word lengths 4, 6, and 8, and the rows of panels indicate distributions for launch sites -1, -3, -5, and -7.

Model predictions are generally in good agreement with the experimental data (see Figure S3). Model simulations reproduced the effects a) that the maxima of the landing site distributions were shifted toward the word beginning for large launch site distances and were shifted toward word endings for small launch site distances and b) that the variance of landing site distributions increased with increasing launch site distance and word length.

Thus, effects of saccade range error were clearly present in the simulated data for both shuffled and normal text.

In addition, the simulated data reproduced differences in landing site distributions between shuffled and normal text reading. Maxima of landing site distributions were shifted toward word beginnings for readers of shuffled text, and the shuffled-SWIFT model reproduced this shift. The shift was mainly present for small (launch sites -1, -3, -5), but not so much for large launch site distances (see launch site -7), indicating that the effect of launch site distance on the maxima of landing site distributions was reduced for shuffled text. Also, variances of landing site distributions were somewhat reduced during shuffled text reading. All of these effects were also visible in the model simulations.

3 Refixation Probability

Distributions of refixation probabilities over different landing positions indicate the optimal viewing position (OVP) during reading (Vitu et al., 2001). The landing position that is associated with the minimal refixation probability indicates the location that is optimal to process the fixated word during one fixation. In the SWIFT model (see also Engbert et al., 2005), the optimal viewing position emerges as fixations are distributed over landing sites according to assumptions about oculomotor control (McConkie et al., 1988). The assumption of a processing gradient is then sufficient to reproduce the U-shaped forms of the refixation distributions.

For long words, the model produces refixations as long words do not fit into the perceptual span and therefore need to be refixated for complete word processing. Short words, however, fully fit into the perceptual span, and no refixations should be needed to complete visual word processing. The SWIFT model (Engbert et al., 2005) assumes that the random saccade timer also triggers saccades early for short words such that refixations are necessary for complete processing. The SWIFT 3 model qualitatively reproduced refixation probabilities during normal and shuffled text reading (see Figure S4). For normal text reading, the distributions are nicely met by model simulations. The shuffled-SWIFT model correctly reproduced the observed increase in refixation probabilities as compared to normal text reading. However, refixation probability at word centres was overestimated by shuffled-SWIFT, and refixations were underestimated at word beginnings. Note, however, that the effect of landing position was not included in the parameter fits.

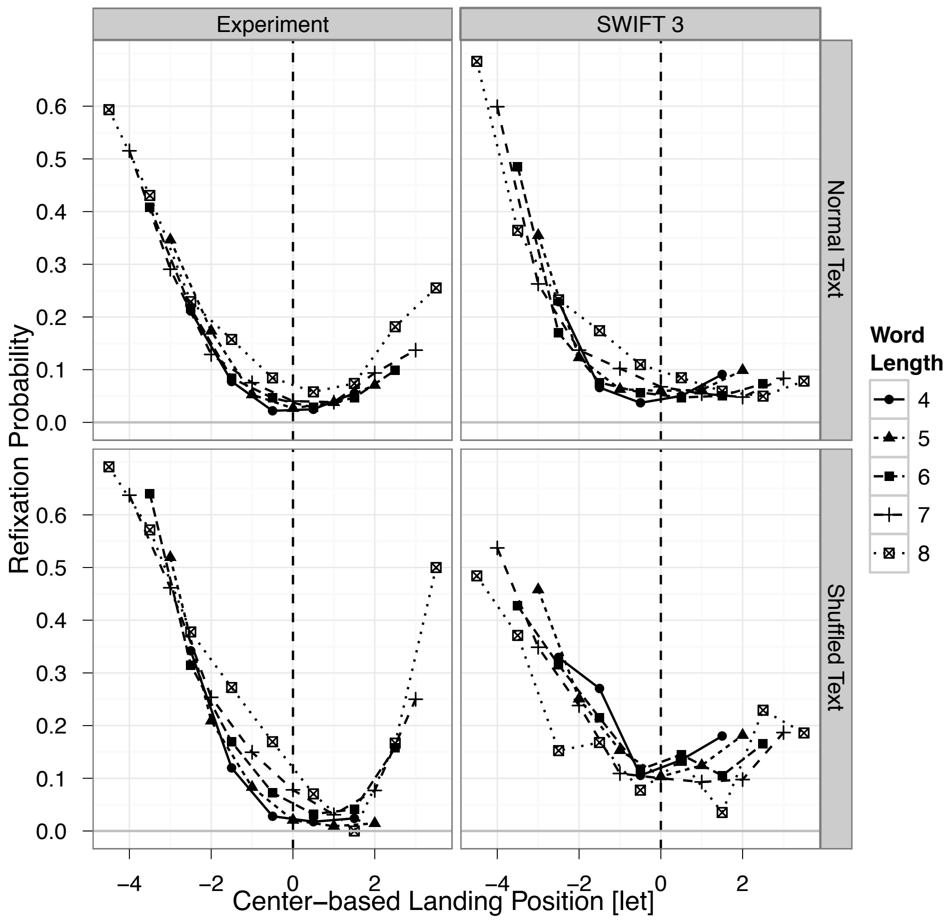

Figure S4

Refixation probabilities after an initial fixation in firstpass as a function of center-based landing position plotted for different word lengths. Experimental data (left panel) show U-shaped curves without an influence of word length. In the model simulations (right panel) these curves are qualitatively reproduced.

4 Inverted Optimal Viewing Position

Based on refixation results for the OVP, one may expect that fixation durations are shortest for fixations at word centers and longer at the edges of words. This, however, is not the case. Vitu and colleagues (2001) were the first to report that fixation durations are longer for fixations at word centers and shorter and the edges of words, which was called an *inverted* OVP effect (IOVP) of fixation durations (see also Nuthmann et al., 2005; Kliegl et al., 2005). For single fixation durations, the SWIFT model explains the IOVP effect via error-correcting after misguided saccades (Engbert et al., 2005; Nuthmann et al., 2005). If a saccade fails the intended word target and lands on a neighboring, unintended word, then immediately a new saccade program is triggered, which can potentially lead to error correction. The likelihood for mislocated fixations is highest at word boundaries, at the first or last letters for each word. This mechanism reduces mean fixation durations at word edges (see Figure S5), which can explain the single fixation duration IOVP effect (Engbert et al., 2005).

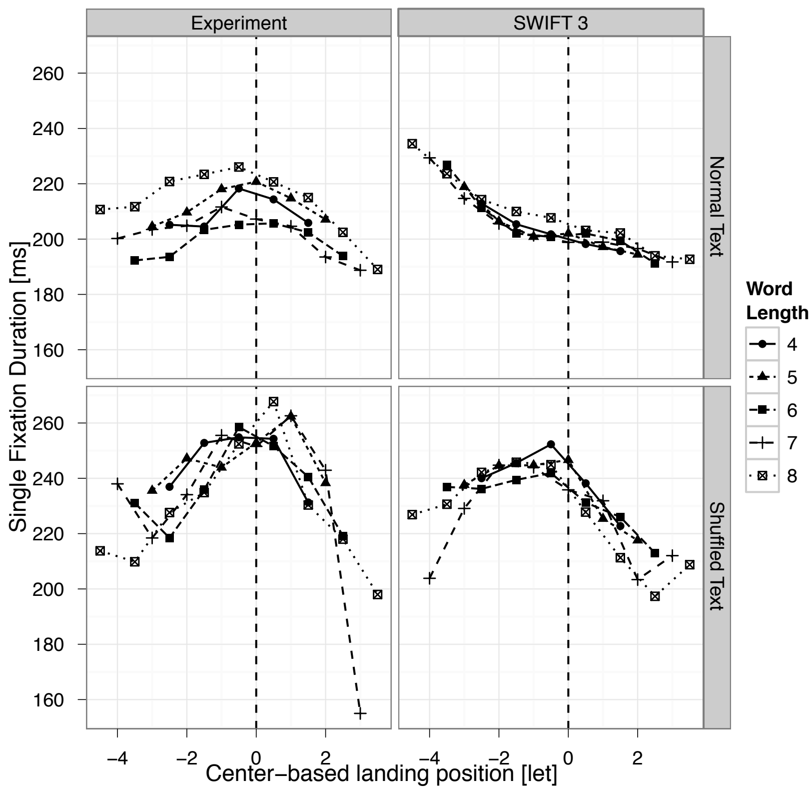

Figure S5

Effects of inverted optimal viewing position for single fixation durations as a function of initial landing site. Effects are shown for model simulations (right panels) and experimental data (left panels), for the reading of normal text (upper panels) and the reading of shuffled text (lower panels).

In two fixation cases, an IOVP effect is observed for the first fixation duration. Plotting the average second fixation duration as a function of first fixation landing site shows a U-shaped effect (Figure S6). Assuming error-correction after misguided saccades is not sufficient to explain these effects. The SWIFT (Engbert et al., 2005) introduces an explanatory mechanism for this complicated pattern of first and second fixation durations: saccade latencies are modulated by intended saccade length. This assumption is motivated by findings from neurophysiology showing that programming a very short saccade is a difficult task for the oculomotor system (Adams et al., 2000; Kalesnykas & Hallett, 1994; Wyman & Steinman, 1973) because an extremely short neuronal pulse must be produced by the brainstem saccade generator (e.g., Spark, 2002). This additional assumption is sufficient to produce the compensatory interaction between first and second fixation durations (see Figure S6; for separate simulations involving each mechanism, see Engbert et al., 2005).

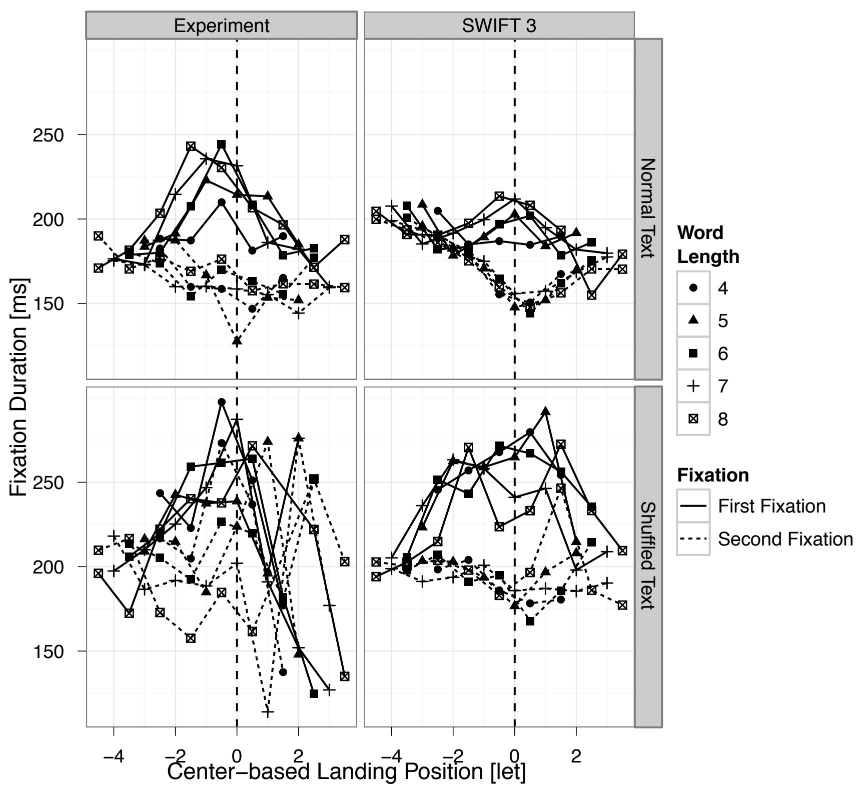

Figure S6

Effects of inverted optimal viewing position for first and second fixation durations in two fixation cases, as a function of initial landing site. Effects are shown for model simulations (right panels) and experimental data (left panels), for the reading of normal text (upper panels) and the reading of shuffled text (lower panels).

For shuffled text reading, the SWIFT model makes the clear prediction that the single fixation duration IOVP should be stronger for longer average fixation durations. This prediction is based on the fact that the mechanism triggering error-correcting saccades works at a fixed speed, independent of the average fixation durations in a task. Fixations at word edges should be relatively independent from cognitive processing demands and constant over different tasks. Fixations at word centers, to the contrary, should be primarily under control of the random timer, and thus adapt to varying task difficulties. This prediction from the SWIFT model is displayed in Figure S5 (right panel), and the findings for shuffled text reading qualitatively correspond to the model prediction. For normal text reading, the model did not capture the IOVP effect in single fixation durations well, presumably because the IOVP effect was not included into the procedure for finding optimal model parameters.

The SWIFT model also makes the analogous prediction that the IOVP effect in first fixation durations should be enhanced during reading of shuffled text. During shuffled text reading, readers make shorter saccades on average, and accordingly saccade latencies are more strongly reduced. This prediction from the SWIFT model, as displayed in Figure S6, was also supported by the experimental results, as the first fixation duration IOVP effect was stronger for shuffled than for normal text reading. Model predictions concerning the IOVP effect were well in line with the observed data.

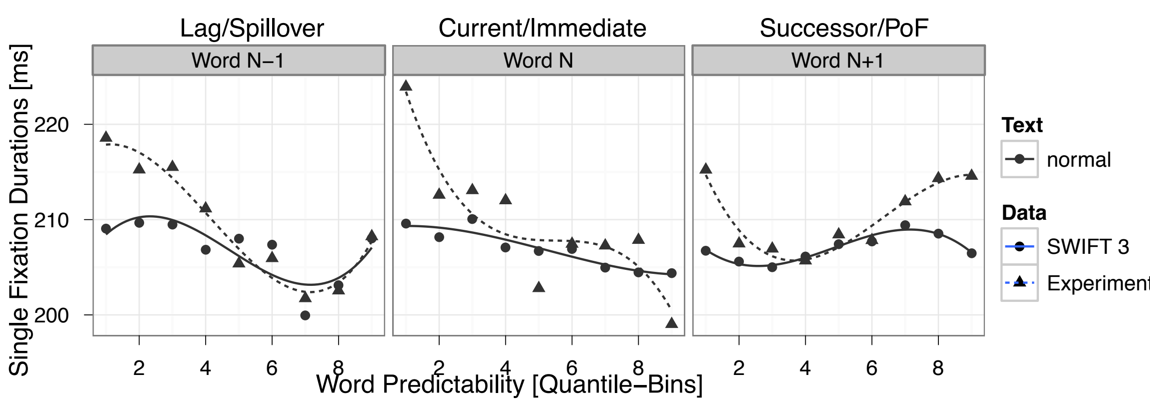

Figure S7

Spatially distributed effect of word predictabilities of words *N*-1, *N*, and *N*+1 on single fixation durations on word *N* for observed (triangles, dashed lines) and simulated (points, solid lines) data. Continuous word predictabilities were categorized into nine quantile-based bins.

5 Word predictability effects in normal text reading

In normal text reading, fixation durations are influenced by whether it's possible to predict upcoming words from their preceding context. Single fixation durations are longer on high predictable words than on low predictable words, and we replicated this standard finding for our experimental data on normal text reading (see Figure S7). Beyond the current-word predictability effect, word predictability also shows effects of distributed processing: single fixation durations are shorter if the last word N-1 was highly predictable and longer if word N-1 was of low predictability. The effect of upcoming word N+1 predictability on fixation durations on word N (i.e., successor effects), however, is reversed (Kliegl et al., 2006): fixation durations are longer before high predictable words, which may indicate processes of memory retrieval for the predicted upcoming word. Although predictability effects were somewhat stronger in observed than in simulated data, the SWIFT 3 model qualitatively reproduced distributed effects of word predictability on single fixation durations (see Figure S7).