Journal of Experimental Psychology: Human Perception and Performance

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Online First Publication, February 18, 2013. doi: 10.1037/a0031647

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0096-1523/13/$12.00 DOI: 10.1037/a0031647

Evidence for Direct Control of Eye Movements During Reading

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It is well established that fixation durations during reading vary with processing difficulty, but there are different views on how oculomotor control, visual perception, shifts of attention, and lexical (and higher cognitive) processing are coordinated. Evidence for a one-to-one translation of input delay into saccadic latency would provide a much needed constraint for current theoretical proposals. Here, we tested predictions of such a direct-control perspective using the stimulus-onset delay (SOD) paradigm. Words in sentences were initially masked and, on fixation, were individually unmasked with a delay (0-, 33-, 66-, 99-ms SODs). In Experiment 1, SODs were constant for all words in a sentence; in Experiment 2, SODs were manipulated on target words, while nontargets were unmasked without delay. In accordance with predictions of direct control, nonzero SODs entailed equivalent increases in fixation durations in both experiments. Yet, a population of short fixations pointed to rapid saccades as a consequence of low-level information at nonoptimal viewing positions rather than of lexical processing. Implications of these results for theoretical accounts of oculomotor control are discussed.

Keywords: stimulus-onset delay, oculomotor control, fixation durations, sentence reading

Efficient reading requires the coordination of oculomotor control and word recognition. On the one hand, fixation durations must be long enough to accumulate sufficient information about the meaning of the words readers view. On the other hand, unnecessarily long dwell times of the eyes would make the reading process inefficient. Time constraints associated with saccade programming and word recognition during normal reading leave little doubt that saccades are programmed in parallel to lexical processing (see Rayner & Pollatsek, 1989, Figure 5.2). Visual (e.g., amount of contrast, font size), lexical (e.g., frequency), and contextual (e.g., predictability) properties of words yield a graded effect on fixation durations (e.g., as word frequency decreases, fixation durations increase; see Rayner, Pollatsek, Ashby, & Clifton, 2012, for a review), but the termination of a fixation is a discrete event triggered by the execution of a saccade program that was initiated about 135 ms earlier (Becker & Jürgens, 1979).[1] There are several mutually nonexclusive proposals that account for the initiation of a new saccade program. For instance, principles of high-level cognitive control (e.g., lexical access, syntactic processing, Reichle, Warren, & McConnell, 2009) or autonomous, possibly random, generation of saccades (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005) have strongly shaped our understanding of eye movement control in reading. Other important mechanisms may involve oculomotor error (e.g., reafference, Nuthmann, Engbert, & Kliegl, 2005) or low-level sensory information (e.g., saccadic inhibition, Reingold & Stampe, 2004; word boundaries, Vitu, Lancelin, & Marrier d'Unienville, 2007). The different options of saccade control can be largely classified into mechanisms of direct and indirect control, which can rely on

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This research was made possible by a Humboldt Research Award from the Alexander von Humboldt Association that enabled K. Rayner to be a Visiting Professor at the University of Potsdam, as well as by the Deutsche Forschungsgemeinschaft (DFG) grant FOR868/1, that enabled M. Dambacher to be a visiting researcher at the University of California, San Diego (where the research was conducted). Further support was provided by Grant HD26765 from the US National Institute of Health. We thank John Henderson, Eyal Reingold, Hans Trukenbrod, and Françoise Vitu for their valuable comments on a prior draft. Data and R scripts are available at the Potsdam Mind Research Repository (http://read.psych.uni-potsdam.de/pmr2).

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[1] Estimates vary from 100–150 ms (e.g., double-step paradigms; see Schall & Thompson, 1999) to 150–175 ms (reading-like tasks; see Rayner, Slowiaczek, Clifton, & Bertera, 1983).

both lexical and nonlexical levels of word processing (Reingold, Reichle, Glaholt, & Sheridan, 2012). However, it is not clear how they are orchestrated to efficiently extract relevant information from a text during reading. The present experiments were designed to shed new light on this question and to provide empirical constraints for theoretical proposals.

A useful tool to test assumptions about the link between mind and eye is the stimulus-onset delay (SOD) paradigm. Here, a critical stimulus—for instance, text (Morrison, 1984; Rayner & Pollatsek, 1981) or scenes (Henderson & Pierce, 2008; Nuthmann, Smith, Engbert, & Henderson, 2010)—is visually masked during the execution of a saccade. At the end of the saccade (i.e., after fixation onset), the stimulus reappears after a certain delay. The rationale behind this procedure is that stimulus processing can only start after its visual features have become available. Thus, from the perspective of a direct eye−mind link, the initiation of a new saccade is delayed due to stimulus inaccessibility at the beginning of a fixation, resulting in an increase in fixation durations. Indeed, the strictest direct-control assumption predicts that the increase of fixation durations is equal to the onset delay if no other information is used to initiate a saccade (i.e., a slope of 1 for the regression of fixation duration on SOD). At the other extreme, saccade latencies would be completely independent of the level of stimulus processing (i.e., a slope of 0) if saccade programs are triggered at random (parameterized according to some distributional assumptions). Of course, intermediate slopes are also a plausible outcome. They could result from a mixture of the two extreme options. For example, a proportion of autonomously triggered saccade programs may "escape" inhibitory influences on saccade initiation due to local processing difficulties. Or some cognitive processing may be carried out in parallel to the delay reducing the amount of total processing required after stimulus onset, leading to a shortening of fixation times.

Results of the pioneering SOD reading studies have provided evidence for significant slopes, but smaller than a slope of 1, roughly in agreement with the "mixed" account. For instance, in the initial series of SOD experiments, Rayner and Pollatsek (1981) used differently sized masks to cover parts of a sentence during each saccade. On fixation, the mask was removed after a delay (0, 25, 50, 100, 200, or 300 ms) such that the entire sentence was available. Rayner and Pollatsek found that fixation durations generally increased with onset delay. Although this was taken as evidence that some fixations are under direct control, other fixation durations were actually shorter than the long onset delays of 200 and 300 ms. In fact, with these long SODs, the distributions of fixation durations were bimodal because they showed a considerable proportion of anticipatory saccades that must have been programmed during the masking period or even during the previous fixation. Further, the increase in fixation durations was smaller than the onset delay. With delays of 0, 25, 50, 75, and 100 ms (see their Experiment 3), fixation durations increased with a slope of 0.61 when onset delay was fixed for all words in a sentence, and with a slope of 0.51 when onset delay varied randomly between words.

In a similar study essentially replicating these findings, Morrison (1984) also found a large proportion of anticipatory saccades terminating fixations before the mask was removed. Further, the onset delay did not equally translate into the increase in fixation durations; the slopes across SODs (25, 50, 200, 350 ms) ranged between 0.77 and 0.88 for different conditions after anticipatory saccades had been removed. To account for these findings, Morrison proposed that once the foveal word is sufficiently processed, attention shifts to the subsequent word before a saccade terminates the current fixation. This covert attention shift permits preprocessing of the parafoveal word while a saccade is programmed in parallel. As a consequence, a high level of parafoveal preprocessing substantially reduces the required inspection time on the subsequent word, resulting in relatively short fixation durations or in saccades that may be executed even before the mask is removed. This proposal strongly influenced later computational models of eye-movement control during reading. For instance, the E-Z Reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2006) implements the principle of parafoveal preprocessing to account for short fixations on or skipping of subsequent words.

More recently, Inhoff, Eiter, and Radach (2005) and Hohenstein, Laubrock, and Kliegl (2010) manipulated SOD of the parafoveal word $n + 1$ relative to the start of fixations on word n. In Inhoff et al.'s experiment, gaze durations increased, with a slope of 0.57 across SODs of 70, 140, and 210 ms; they did not find an effect for the increase between 0 (control condition) and 70 ms SOD. In Hohenstein et al., gaze durations on target word $n + 1$ increased roughly linearly, with slopes ranging between 0.47 and 0.61 for SODs from 20−125 ms (across four experiments).

SOD effects on fixation durations have also been examined in scene viewing. A visual mask replaced an image during the saccade preceding a critical fixation and was removed after a delay. In several experiments, bimodal distributions consistently revealed two populations of fixation durations: one that increased with SODs and one that was largely unaffected by SODs. Of note is that modal values of the former distributions increased with a slope of approximately 1 (Henderson & Pierce, 2008; Henderson & Smith, 2009). Nuthmann and Henderson (2012; see also Luke, Nuthmann, & Henderson, 2012) recently reported comparable results in a reading experiment on multiline passages, in which the entire text was masked for a certain delay during the saccade prior to every sixth fixation. Thus, there is evidence that eye movements in both scene viewing and reading are characterized by mixed control: some fixations directly depend on useful visual information, whereas other saccades are triggered independently from stimulus processing.

Yet, current knowledge of the mixed control perspective is based on experiments permitting both foveal and parafoveal viewing. None of the previous SOD studies implemented a design in which saccade timing depended completely on foveal lexical information: Rayner and Pollatsek (1981); Morrison (1984), as well as Nuthmann and Henderson (2012) did not prevent parafoveal preprocessing of target words, and Inhoff et al. (2005) and Hohenstein et al. (2010) manipulated SOD for the parafoveal word. As mentioned above, however, parafoveal processing can critically affect fixation durations, and may therefore distort conclusions about the nature of oculomotor control. To provide a strong test of the assumption that eye movements are directly controlled by lexical processing of the foveal word, we employed a version of the SOD paradigm that ruled out any preprocessing due to parafoveal vision and that used target words with minimal predictability from prior sentence context to eliminate another potential source of preprocessing. Unlike previous SOD studies, we implemented word-based instead of character-based masks in sentences. That is, we used a one-word moving window technique (McConkie & Rayner, 1975) in which only a single word at a time was visually processed: When the eyes landed on a word, the mask was removed only for this particular word while the rest of the sentence remained masked.

Experiment 1

In Experiment 1, SODs were constant for all words in a sentence. On fixation, each word was unmasked with one of four delays (i.e., 0, 33, 66, or 99 ms) and was remasked immediately after the eyes moved on to the next word. According to predictions from a direct control perspective, we expected that onset delays would be fully reflected in inspection times. Thus, fixation durations were predicted to increase as a function of SOD with a slope of 1.

Method

Subjects. Twenty-two students at the University of California, San Diego, received course credit for participation. All were native speakers of English, had normal or corrected-to-normal vision, and were naive about the purpose of the experiment.

Stimuli and design. A total of 120 English sentences formed the stimulus materials. Sentences were 8−15 words long. Each sentence contained a low predictable target noun between the third and twelfth word position (M_{position} = 7.68, *SD* = 1.68). The sentences were adapted from prior studies with the constraint that the target word was never identified in a modified cloze task more than 3% of the time. Targets were four to seven letters long (M_{length} = 5.38, *SD* = 0.69; number of four- to seven-letter targets: 6, 72, 34, and 8, respectively) and their frequencies varied from 0.38−550.40 occurrences per million ($M_{\text{frequency}}$ = 50; *SD* = 82); frequency norms were assessed from the Corpus of Contemporary American English comprising more than 400 million tokens (Davies, 2008). The correlation of target word length and logarithmic frequency was not significant, $r = -.070$, $t(118) = -.767$, $p = .444$.

A one-word moving window paradigm with delayed stimulus onset was used for sentence presentation (McConkie & Rayner, 1975; Rayner & Bertera, 1979). Every word in a sentence was initially masked by an *x*-string of corresponding length; this mask maintained low-level information of stimulus size and word boundaries but prevented any kind of lexical processing. A word was unmasked after a delay of 0, 33, 66, or 99 ms relative to the time the eyes crossed an invisible boundary between adjacent words, and was immediately remasked after the word was left (i.e., a variant of the boundary paradigm, Rayner, 1975). Therefore, stimulus onset was not delayed for any refixation within a word. The display changes associated with stimulus unmasking took about 7 ms to execute following the delay period. Onset delays were constant for all words in a sentence. To reduce the probability of fixations very close to a boundary, potentially resulting in unintended display changes, words were separated by two spaces, and the boundary was placed between them. For every subject, 30 sentences were presented in each of the four SODs in randomized order; SOD conditions attributed to each sentence were counterbalanced across participants.

Procedure. Participants were instructed to read the sentences for comprehension. They were informed that words would be masked unless they were fixated and that words would be remasked after the eyes moved on. However, subjects were naive with respect to the SOD. Eight practice trials before the main experiment familiarized them with the task. Every trial started with a gaze box (25 × 25 pixels, 0.8° of visual angle) vertically centered on the left side of the monitor. When the eye tracker detected a valid fixation in the gaze box, a masked sentence was presented on the center line, with the left edge of the first character situated at the left edge of the gaze box. After reading a sentence, subjects pressed a button on a controller, which initiated either the next trial (67%) or a two-option multiple-choice question to test sentence comprehension (33%, accuracy of responses: 92%). The experiment took approximately 45 minutes.

Eye movement recording. Eye movements were recorded using an EyeLink 1000 eye tracker that sampled the position of the right eye at 1000 Hz. Subjects were seated 60 cm from the monitor, with their heads positioned on a chin rest. Stimuli were presented in Courier New (font size: 14; black font on a white background) on an Iiyama 454 Vision Master Pro CRT monitor (19 in.; refresh rate: 150 Hz; resolution: 1024 × 768). Letters subtended 0.29° of visual angle. Calibration was performed on a standard three-point grid.

Data processing and analyses. After deleting trial initial and final fixations as well as fixations on sentence initial and final words, reading data yielded a total of 31,729 fixations. Of these fixations, 3,999 were on target words. These fixations were initially filtered for first-pass reading, yielding 3,409 data points. Next, all fixations on target words with at least one fixation duration less than 50 ms (15 words) or greater than 750 ms (9 words) were excluded. Fixations on target words were also excluded from analysis if they contained a first-pass blink or if there was a blink during an immediately preceding fixation (fixations on 14 words). Further, target fixations were eliminated if there were problems with display changes. For nonzero SODs, we excluded display changes with temporal inaccuracies that exceeded ±17 ms (i.e., 50% of SOD steps in either direction) relative to the start of the postchange fixation; the majority of these errors were due to display changes that completed earlier than intended. For the 0-ms SOD, we included only targets with display change times between −30 and 0 ms relative to fixation onset; this filter ensured that display changes in the 0-ms SOD condition were executed during saccades such that their visibility was minimized (cf., Matin, 1974; Slattery, Angele, & Rayner, 2011). Latencies of effective display change initiation relative to the onset of the first fixation on the target word are listed in Table 1. Temporal errors leading to data exclusion occurred on 10% and 14% of target display changes in the nonzero SODs and the 0-ms SOD, respectively. We also discarded sentences with display change problems on any word prior to the target (14%).

Table 1
Mean Times of Effective Display Change Initiation Relative to First Fixation Onset on the Target Word Across SOD Conditions and Word Length in Experiments 1 and 2

	SOD in Experiment 1				SOD in Experiment 2			
Length	0 ms	33 ms	66 ms	99 ms	0 ms	33 ms	66 ms	99 ms
4	−11	28	60	93	−10	28	62	95
5	−11	28	61	94	−10	28	61	94
6	−12	27	62	94	−11	28	62	94
7	−12	28	63	95	−11	29	62	95

Note. Standard errors of means were smaller than 1.2 ms in all cases. SOD = stimulus-onset delay.

Finally, we excluded fixations that were preceded or followed by saccades more than 25 characters as well as those that were followed by a regression. This screening resulted in 2,238 fixations on target words.[2] The number of fixations was similar across conditions (i.e., 607, 572, 545, and 514 fixations for SODs of 0, 33, 66, and 99 ms, respectively).

From these data, first fixation durations (FFDs, the first fixation on a word independent of how many other fixations were made), and gaze durations (GDs, the sum of all fixation durations on a word before moving to another word) were determined for target words. Linear mixed models (LMMs) implemented in the lme4 package (Bates & Maechler, 2010) were used for statistical analyses of logarithmic fixation durations. These models provided estimates of SOD effects, simultaneously taking into account fixed effects of initial landing position[3] on the target (linear and quadratic trends) as well as of printed word frequency and length; subjects and words were specified as random effects.[4] For LMMs, effects of onset delay were parameterized with three contrasts between "neighboring" SODs (i.e., the difference between 0-ms and 33-ms SODs; analogously between 33-ms and 66-ms SODs, and between 66-ms and 99-ms SODs). Further, considering the low number of four- and seven-character targets, word length was specified as a two-level factor (short: four to five letters, long: six to seven letters) and also parameterized as a contrast (i.e., the difference between short and long words). Any t values larger than 2 were interpreted as significant because, given the number of subjects and the number of observations per subject in our experiment, the t distribution effectively approximated the normal distribution. All fixed effects reported as significant were also significant according to Markov chain Monte Carlo (MCMC) based 95% highest posterior density (HPD) intervals, using the *mcmcsamp* with $N = 10{,}000$ samples and *HPDinterval* functions of the lme4 package; corresponding p values are provided in the LMM tables (Tables 3 and 5). Data were visualized using the ggplot2 package (Wickham, 2009). Both packages run in the R system for statistical computing (R Development Core Team, 2011).

Results and Discussion

Distributions and mean fixation times. Density plots of fixation times (Figure 1) indicated that nonzero delay distributions largely lined up with SODs: A longer SOD resulted in a right shift of the distributions. Accordingly, mean fixation times (Table 2) increased with SOD step ups from 33 to 99 ms. Specifically, the increase of 33 ms was rather precisely reflected for GD in the nonzero SOD conditions, while it was somewhat smaller for FFD, especially in the 99-ms versus the 66-ms SOD. Unexpectedly, though, fixation times were longer in the 0-ms than in the 33-ms SOD. The 0-ms SOD distribution peaked somewhat later than the 33-ms SOD distribution and essentially lay between the distributions of the 33-ms and 66-ms SODs (see Figure 1a). Potential reasons for this surprising and novel pattern are discussed below (see General Discussion). Yet, the relatively longer fixation times in the 0-ms SOD resulted in an underestimation of the linear slopes[5] for fixation times as a function of SOD; they were estimated to be considerably smaller than 1 (FFD: 0.40; GD: 0.56). Slopes across the nonzero delays were clearly steeper and were close to 1 for GD (FFD: 0.70; GD: 0.98).

LMM results. Results of LMMs, including SOD, initial landing position, word frequency, and length as predictors, are listed in Table 3. In line with distributions (see Figure 1) and mean fixation times (see Table 2), FFDs and GDs were significantly longer in the 0-ms compared to the 33-ms SOD. For all other contrasts between nonzero SODs, FFDs and GDs increased significantly with SODs.

Apart from these delay-induced effects, fixation durations were reliably modulated by the initial landing position in the target word. Specifically, the quadratic trend for GD indicated that fixation durations were longest when words were fixated at their beginning, and decreased as the eyes landed toward the word center. At positions close to word ending, GD tended to increase again (Figure 2a, right panel).[6]

Compared to the GD results, FFD showed the inverse pattern. Fixations were shortest at the beginning of words and increased with letter position (see Figure 2a, left panel). The quadratic trend indicated that this increase diminished toward word center. This pattern is compatible with the inverted optimal viewing position (IOVP) effect (Vitu, McConkie, Kerr, & O'Regan, 2001), that is, the phenomenon that reading fixations are shorter at word edges than at word center. One explanation for the IOVP effect is that corrective saccades are executed very quickly when the eyes land away from the intended optimal position for lexical processing, that is, slightly left from the word center (Nuthmann et al., 2005; Nuthmann, Engbert, & Kliegl, 2007). It has also been suggested that reading fixations are generally shorter at locations that are expected to be less optimal for letter extraction (Vitu et al., 2001; Vitu et al., 2007).[7] Accordingly, rapid saccades (or short fixations) at word initial positions are largely triggered by low-level visual information. For FFD, the interaction of Quadratic Landing Position × Contrast between 0-ms and 33-ms SOD points to a sizable (inverse) delay effect at more central landing positions, whereas fixation durations for the two conditions were similar toward the beginning of words.

[2] The reason for the relatively large proportion of dropped data is the rather conservative exclusion criterion on display change timing. Note, however, that the basic pattern of results in Experiments 1 and 2 also holds for more liberal screening criteria.

[3] Landing position was calculated as the initially fixated letter position divided by the total number of letters. Hence, after centering, landing position ranged from −0.5 to 0.5 with 0 denoting word center. On average, the eyes initially landed left from word center, near the preferred viewing location (Rayner, 1979), in all conditions (0-ms stimulus-onset delay [SOD]: $M = -0.10$, $SE = 0.01$; 33-ms SOD: $M = -0.11$, $SE = 0.01$; 66-ms SOD: $M = -0.12$, $SE = 0.02$; 99-ms SOD: $M = -0.13$, $SE = 0.01$). Landing positions did not differ between SODs, $F(3, 63) = 1.50$, $p = .22$.

[4] Linear mixed models (LMMs) did not include random slopes of fixed effects. Random slopes of stimulus-onset delay conditions did not improve model fits in Experiment 1, first fixation duration (FFD): $\Pr(>\chi^2) = .50$; gaze duration (GD): $\Pr(>\chi^2) = .09$, or in Experiment 2, FFD: $\Pr(>\chi^2) = .35$; GD: $\Pr(>\chi^2) = .59$. Including the other predictors as random slopes led to false convergence of the LMMs.

[5] Slopes were computed on the basis of unaggregated fixation durations using a linear mixed model with stimulus-onset delays as fixed and participants (Experiments 1 and 2) as well as words (Experiment 1 only) as random effects.

[6] Effects of landing position are illustrated as quantiles of the overall landing site distribution; note, however, that linear mixed model results are based on continuous values of landing position.

[7] Although the inverted optimal viewing position effect is often characterized by an inverted U-shaped function (e.g., Nuthmann et al., 2005; Nuthmann et al., 2007; Vitu et al., 2001), we did not observe much of a decrease for first fixation duration on positions toward word endings, presumably because word final positions in our data were fixated in only very few cases. Specifically, less than 25% of all first fixations landed in the second half of words, such that there were very few data points at the very end of words.

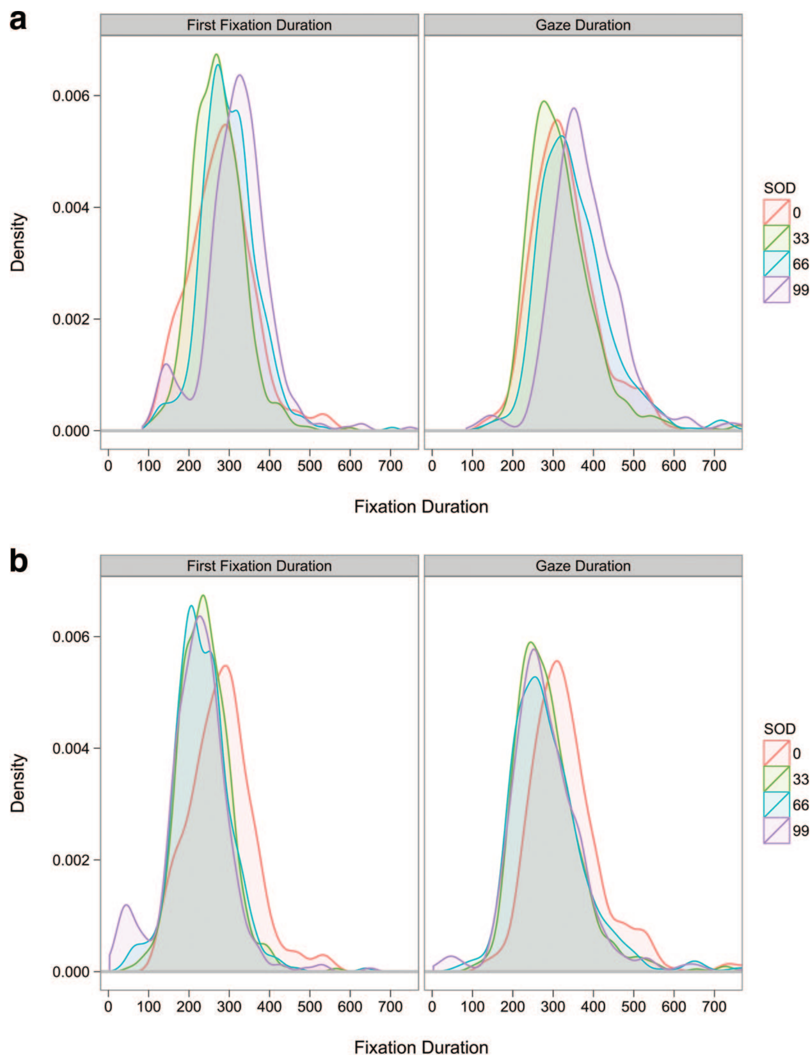


Figure 1. Distributions of first fixation and gaze durations on target words in Experiment 1. Density plots across four stimulus-onset delay conditions (panel a). Density plots of fixation durations relative to target word onset (panel b).

Fixation durations (i.e., FFD and GD) were also shorter for high- than for low-frequency words, an effect that is in line with numerous earlier reports (e.g., Inhoff & Rayner, 1986; Kliegl, Grabner, Rolfs, & Engbert, 2004; Kliegl, Nuthmann, & Engbert, 2006; Rayner & Duffy, 1986; see Rayner, 1998, 2009, for further summaries). The result is also in accord with a direct control perspective because it shows that fixation durations are modulated by lexical information after mask offset. In addition, an interaction of Frequency × Contrast between 99-ms and 66-ms SOD indicated a stronger frequency effect for GD in the 99-ms than in the 66-ms SOD (Figure 3b). Thus, the data provide some evidence that, with long-onset delays, processing related to lexical information (e.g., predictions based on prior sentence context and visual mask length) may have started and affected fixation duration. This suggests that top-down processes can contribute to eye movement control, which is associated with processing lexical information.

Table 2
Mean Fixation Durations and Standard Errors on Target Words Together With Difference Scores (Δ) Between SODs and Number of Target Fixations in Experiment 1

	First fixation duration			Gaze duration			*N* fixations	
SOD	*M*	*SE*	Δ	*M*	*SE*	Δ	*M*	*SE*
0	282	7		336	8		1.27	0.04
33	271	6	−11	322	7	−14	1.27	0.04
66	297	6	26	355	9	33	1.30	0.03
99	316	7	19	386	7	31	1.38	0.04

Note. SOD = stimulus-onset delay.

Further, and contrary to previous findings (e.g., Kliegl et al., 2004; Kliegl et al., 2006), an effect of word length revealed longer FFDs for short than for long targets; none of the interactions of Length × SOD were significant. Yet, Figure 3a illustrates that this effect was numerically strongest in the 0-ms SOD, whereas non-zero SODs show only small length-related differences. Accordingly,

Table 3
LMM Effects of SOD, Landing Position (Linear and Quadratic Trend), Logarithmic Frequency, and Word Length in Experiment 1

	First fixation duration				Gaze duration			
	Estimate	*SE*	*t*	*p*	Estimate	*SE*	*t*	*p*
Fixed effects								
(Intercept)	5.73	0.02	282.70	0.000	5.77	0.02	292.32	0.000
SOD (33–0)	−0.05	0.02	−2.57	0.011	−0.04	0.02	−2.25	0.022
SOD (66–33)	0.10	0.02	5.46	0.000	0.11	0.02	5.76	0.000
SOD (99–66)	0.08	0.02	4.32	0.000	0.12	0.02	5.80	0.000
LandPos	0.32	0.04	9.04	0.000	0.08	0.04	2.02	0.042
LandPos^2	−1.07	0.10	−10.36	0.000	1.11	0.11	10.08	0.000
logFrequency	−0.01	0.00	−3.14	0.001	−0.03	0.01	−4.81	0.000
Length (short−long)	0.03	0.01	2.58	0.009	−0.01	0.01	−0.53	0.563
SOD (33–0) × LandPos	0.06	0.09	0.71	0.493	0.01	0.10	0.14	0.895
SOD (66–33) × LandPos	−0.12	0.10	−1.23	0.213	0.04	0.11	0.38	0.696
SOD (99–66) × LandPos	0.11	0.10	1.06	0.289	0.14	0.11	1.32	0.191
SOD (33–0) × LandPos^2	0.83	0.28	3.00	0.003	0.25	0.30	0.85	0.390
SOD (66–33) × LandPos^2	−0.20	0.28	−0.72	0.478	−0.20	0.30	−0.66	0.510
SOD (99–66) × LandPos^2	−0.23	0.29	−0.82	0.387	−0.34	0.31	−1.08	0.277
SOD (33–0) × logFrequency	−0.02	0.01	−1.48	0.130	0.00	0.01	−0.23	0.792
SOD (66–33) × logFrequency	−0.01	0.01	−0.64	0.542	0.01	0.01	1.04	0.286
SOD (99–66) × logFrequency	0.00	0.01	0.01	0.996	−0.03	0.01	−2.24	0.028
SOD (33–0) × Length (short−long)	−0.05	0.03	−1.63	0.107	−0.02	0.03	−0.66	0.498
SOD (66–33) × Length (short−long)	−0.01	0.03	−0.29	0.761	−0.03	0.03	−1.06	0.298
SOD (99–66) × Length (short−long)	−0.01	0.03	−0.23	0.835	0.03	0.03	0.77	0.437
Random effects	*SD*	HPD95 lower	HPD95 upper		*SD*	HPD95 lower	HPD95 upper	
Words	0.029	0.000	0.035		0.045	0.021	0.055	
Subjects	0.089	0.061	0.114		0.084	0.058	0.110	
Residual	0.207	0.201	0.215		0.221	0.215	0.230	

Note. Subjects and words are specified as random factors. LMM = linear mixed models; SOD = stimulus-onset delay; LandPos = landing position; HPD95 = 95% highest posterior density interval.

neither the main effect of length nor any interaction with SOD survived, when the 0-ms SOD was excluded in the LMM ($|t|\text{s} < 1.23$). This pattern suggests that the unexpected pattern of longer fixation durations in the 0-ms compared to the 33-ms SOD was especially driven by short target words (i.e., 4–5 letters).

Landing sites and short fixations. As another prominent characteristic of the data, the distributions of (first) fixation durations, especially for the 99-ms SOD, revealed a population of long fixations, but also a sizable proportion of fixations shorter than 100 ms relative to the display change (FFD: 0.0%, 0.9%, 2.8%, and 8.8%, and GD: 0.0%, 0.0%, 0.7%, and 2.1% of fixations in the 0-, 33-, 66-, and 99-ms SODs, respectively) (see Figure 1a). This observation becomes even more apparent when onset delays are subtracted from fixation durations; that is, when fixation times are computed relative to the onset of the target word (see Figure 1b). Given that the signal of a word reaches the visual cortex about 50 ms after unmasking (e.g., Martínez et al., 1999) and that it takes about 135 ms to program a new saccade (e.g., Becker & Jürgens, 1979), these short fixation durations are unlikely to be modulated by lexical processes. Instead, considering the IOVP effect, a plausible source for the rapid saccades is their initial landing position. That is, the population of short fixations may mainly originate at nonoptimal positions, that is, at the word beginning. To test this idea, we divided FFD distributions into two quantile-based landing zones (word beginning: 0%−25% of word length; word center-to-end: 25%−100% of word length). As expected and shown in Figure 2b, short fixation durations were predominantly triggered when the eyes landed at the beginning of a word. There were very few short fixations when the central region of the words was initially fixated. Thus, a considerable proportion of rapid saccades were launched from nonoptimal viewing positions, a result lending support to the notion of corrective saccades (Nuthmann et al., 2005); indeed, 78% of the short FFDs were followed by a refixation on the target word. Similarly, the perceptual economy hypothesis poses that fixation durations are short when low-level visual information (e.g., the proximity of interword spaces) indicates that little lexical information can be expected; accordingly, saccades are rapidly initiated from landing positions close to word edges (Vitu et al., 2001; Vitu et al., 2007). After all, the population of short fixations may reflect a mixture of these accounts, and our data do not disclose the exact underpinnings of the rapid saccades and the associated IOVP effect. However, with respect to our main goal, namely, to examine the role of direct control in reading, we can conclude that these short fixations were largely detached from lexical processing.

Short fixations have also been considered as the result of preprogrammed saccades. For instance, Morrison (1984) proposed that advanced parafoveal preprocessing of a word to the right of the fixation initiates a saccade program to the second next word, resulting in a short subsequent fixation or skipping. This explanation, however, cannot be true here because lexical information was parafoveally unavailable. It is possible, though, that saccades were preprogrammed independently of parafoveal vision. For example, fixations on the target can be short when a random timer has initiated a saccade program during the pretarget fixation (cf., Nuthmann & Henderson, 2012; Schad & Engbert, 2012; see also General Discussion). However, this does not explain the interdependence of short fixations and nonoptimal viewing position; we therefore suspect that rapid saccades were at least partly triggered by low-level visual information.

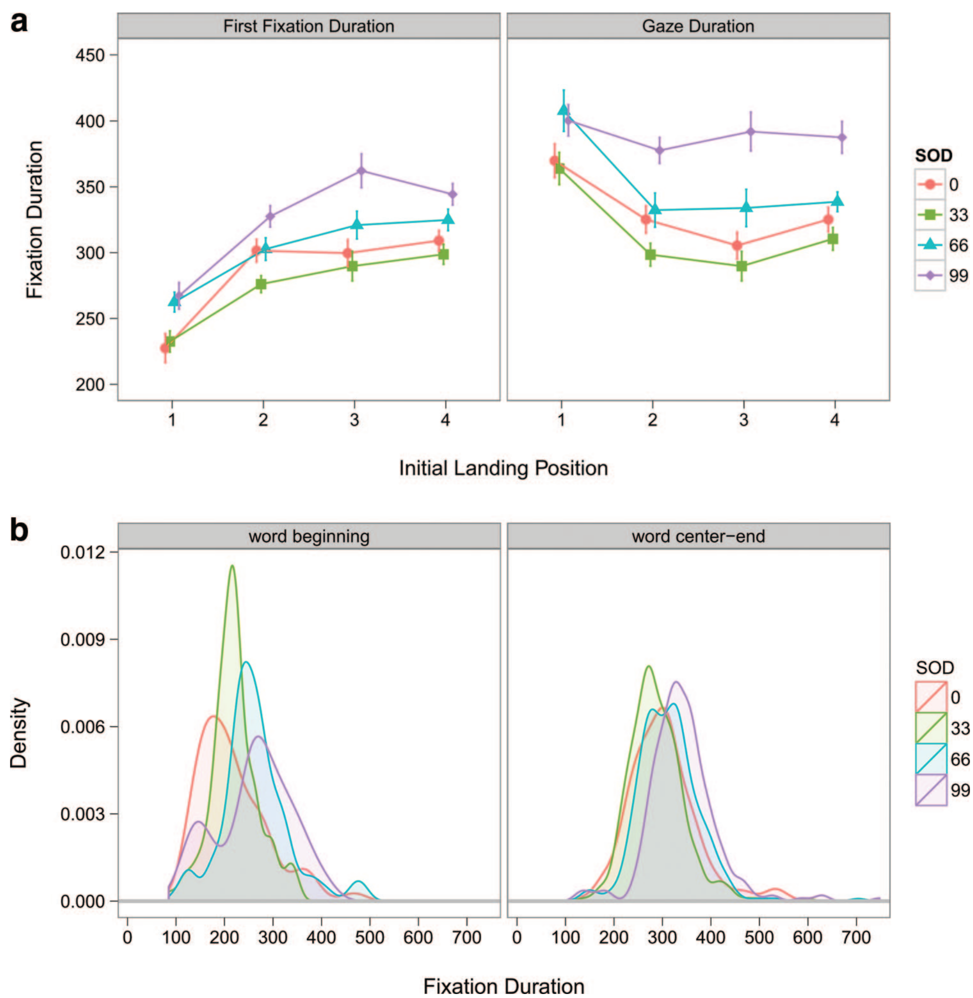


Figure 2. Effects of initial landing position on target words in Experiment 1. First fixation and gaze durations across initial landing positions and stimulus-onset delays. Data points reflect quantiles of the overall landing site distribution. Error bars reflect standard errors (panel a). Density plots of first fixation durations landing close to the word beginning (first quarter) or center-to-end region (second through fourth quarters) (panel b).

It is interesting that the populations of shorter and longer fixation durations appear to be separated by a trough (see Figure 1). A likely reason for this bimodality is saccadic inhibition, that is, the transient inhibition of saccade generation starting around 60–100 ms after the onset of a very noticeable visual stimulus (e.g., a white flash covering the top and bottom third of a monitor; Reingold & Stampe, 1999, 2000, 2004). In fact, Figure 2b (left panel) shows a drop in saccade rates at approximately 150 and 190 ms, for 66- and 99-ms SODs, respectively. That is, 100 ms after the display change turned a masked stimulus into a word, a considerable proportion of saccade programs had been cancelled.[8]

Evidence for direct control? Are the results of Experiment 1 compatible with predictions from direct eye movement control? As stated above, the 33- and 31-ms differences in mean GD reflect quite accurately the differences between the nonzero SODs, but they were shorter than predicted for FFDs at the longest delay of 99 ms (see Table 2). This was also expressed in a slope smaller than 1 for the regression of FFD on SOD even after exclusion of the 0-ms SOD condition (i.e., FFD: 0.70; GD: 0.98).

Yet, the above analyses identified a population of rapid saccades that appeared to be driven by low-level information from suboptimal landing positions (Nuthmann et al., 2005; Nuthmann et al., 2007; Vitu et al., 2001; Vitu et al., 2007). Especially in the 99-ms SOD, a sizable proportion of first fixations landing in the first quarter of targets were terminated within 100 ms after stimulus onset. Evidently, these rapid saccades affected the estimation of delay effects on fixation durations associated with lexical process-

[8] Saccadic inhibition can also account for other characteristics of the distributions. Specifically, Figure 1a illustrates that first fixation duration (FFD) distributions of the 0- and 99-ms stimulus-onset delays (SODs) largely overlap for the shortest fixation durations: Saccadic inhibition did not play a role in the 0-ms SOD (i.e., no visible display change) and had an effect only on longer fixation durations in the 99-ms SOD (i.e., 150−200 ms after fixation onset). In contrast, the leftmost flanks of the FFD distributions in the 66- and 33-ms SODs are much flatter, because saccadic inhibition due to display changes affected the earliest fixation durations. As a consequence, the population of short fixations (i.e., smaller than 100 ms after word onset) among the nonzero delays is largest in the 99-ms SOD condition.

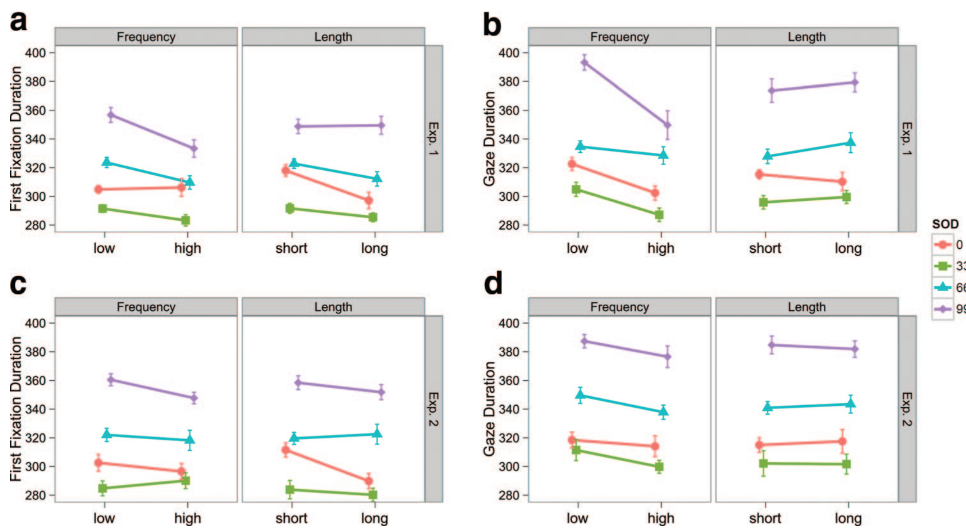


Figure 3. Fixation durations on target words across stimulus-onset delay conditions for two levels of target word frequency and target word length. Error bars reflect standard errors. Plots of word frequency: data points reflect estimates based on linear mixed models (LMMs) after partialing out effects of landing position (linear and quadratic trend) and word length as well as random effects of subjects (Experiments 1 and 2) and words (only Experiment 1). Plots of word length: data points reflect LMM-based estimates after partialing out effects of landing position (linear and quadratic trend), word frequency, and random effects of subjects (Experiments 1 and 2) and words (only Experiment 1). The panels show first fixation durations (FFDs) of Experiment 1 (panel a), gaze durations (GDs) of Experiment 1 (panel b), FFDs of Experiment 2 (panel c), and GDs of Experiment 2 (panel d).

ing. Excluding fixations durations smaller than 100 ms relative to the display change improved the correspondence of nonzero SODs and the increase in FFDs (slope = 0.91; 33-ms SOD: 272 ms; 66-ms SOD: 302 ms; 99-ms SOD: 334 ms) and led to a slope even slightly greater than 1 in GDs (slope = 1.07; 33-ms SOD: 322 ms; 66-ms SOD: 356 ms; 99-ms SOD: 394 ms). This is also apparent in Figure 4a (data for Experiment 1), which displays observed mean fixation times (cf., Table 2) together with LMM-based estimates. After partialing out influences of landing position, frequency, and word length, as well as random effects due to subjects and words, the data clearly reveal a linear course with a slope of approximately 1 across nonzero SODs.

Of note, Figure 4b illustrates that SOD effects were not restricted to target words. In accordance with the constant delays per sentence, the effect of nonzero SODs is nicely reflected in FFDs as well as in GDs on nontarget words. Likewise, the pattern of longer fixation durations in the 0-ms compared to the 33-ms SODs translates to pre- and posttarget words. The observation that inspection times are somewhat longer at target compared to nontarget words in all SOD conditions is presumably a consequence of the constraint that targets were always content words of low predictability whereas word class and predictability were not controlled on other positions.

In summary, the results suggest that eye movements in Experiment 1 were driven by two sources. One was low-level visual information triggering rapid saccades after fixations landed at suboptimal viewing positions. The other source was related to lexical processing (i.e., word frequency) and depended on when this information became available; for this case, unit slopes from regressions of fixation durations on SODs are in line with predictions of direct lexical control.

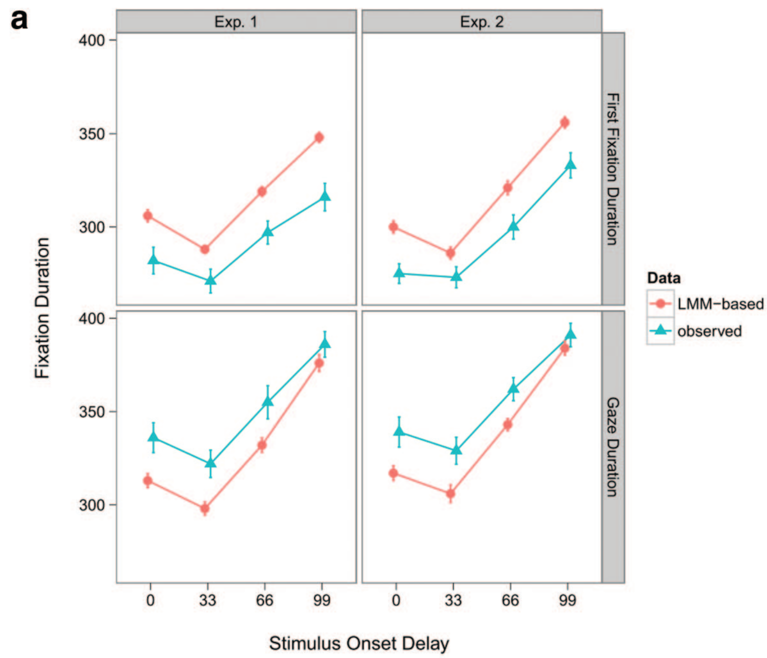
Experiment 2

In Experiment 1, SODs were identical for all words in a sentence. Disregarding short inspection times at nonoptimal viewing positions, the delays translated one-to-one in increases in fixation durations. Yet, target words occurred on average only after the seventh position in sentences. It is therefore possible that saccade timing generally adjusted to the constant delays across the course of target-preceding words, even if oculomotor control was partly independent from lexical processing. In other words, the constant SODs for all words in a sentence might have translated into a corresponding global increase of fixation durations; locally, eye movements may not have been under direct control (Trukenbrod & Engbert, 2011).

We addressed this issue in Experiment 2, in which again all words were masked unless they were fixated. Unlike Experiment 1, though, onsets were delayed only on target words (0-, 33-, 66-, or 99-ms SODs). All other words were always immediately unmasked when the eyes crossed the boundary (i.e., 0-ms SOD). Because subjects were unaware of the existence of target words (or their position), and because SODs varied randomly between sentences, it was impossible to prepare for the infrequently augmented SODs (cf., Henderson & Pierce, 2008). Nonetheless, according to direct control assumptions, fixation durations were expected to capture the target-specific onset delays. Another purpose of Experiment 2 was to replicate the unexpected finding of longer fixation durations in the 0-ms than in the 33-ms SOD condition.

Method

Subjects. Thirty-two students at the University of California, San Diego, received course credit for participating. They were native speakers of English and had normal or corrected-



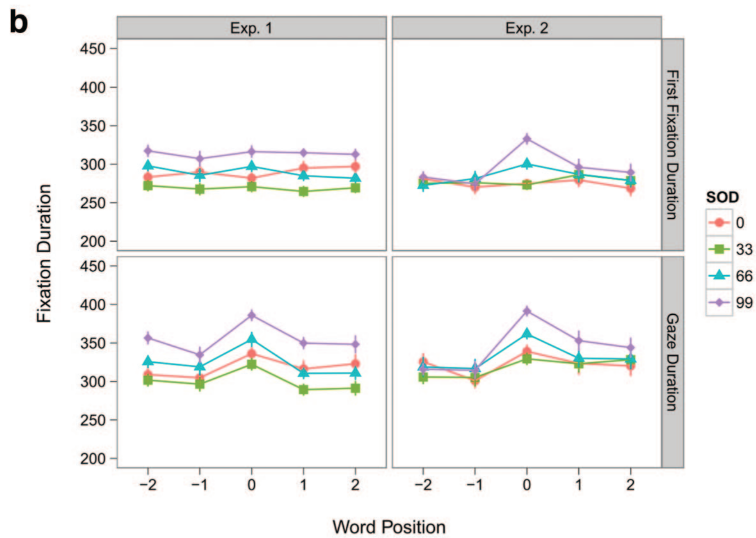


Figure 4. Mean fixation durations on target words across stimulus-onset delay conditions. Means show observed data together with estimates based on linear mixed models after partialing out effects of landing position (linear and quadratic trend), frequency, and word length as well as random effects of subjects (Experiments 1 and 2) and words (only Experiment 1) (panel a). Observed mean fixation durations across five successive words in Experiments 1 and 2. Word position 0 denotes the target word (panel b). Error bars reflect standard errors.

to-normal vision. None of these students had participated in Experiment 1.

Stimuli, recording, and procedure. Stimuli, data recording, and procedure were adopted from Experiment 1. As before, sentences were presented with a one-word moving window procedure, such that every word was masked unless it was fixated. However, unlike Experiment 1, stimulus onset was delayed for 0 ms for all words in a sentence, except for the targets, which were delayed for either 0, 33, 66, or 99 ms. Subjects read sentences for comprehension and responded to multiple choice questions in one third of the trials (accuracy was 91%). Subjects were informed about the masking of stimuli, but were unaware of varying onset delays on target words. The experimental session took about 45 minutes.

Data processing and analyses. Data were processed and analyzed as in Experiment 1. From a total of 58,012 data points (without sentence initial and final words and fixations), screening resulted in 2,357 valid fixations on target words (cf., Method of Experiment 1 and Footnote 2). FFD and GD were statistically analyzed in LMMs, including contrasts of neighboring SODs, initial landing position[9] (linear and quadratic trends), as well as word frequency and length (short: four to five letters, long: six to seven letters) as predictors. In contrast to Experiment 1, however, the specification of words as a random factor did not improve the model. In other words, there was no reliable variance associated with differences in mean durations on words (likelihood ratio tests yielded chi-square values <1 for 1 degree of freedom). Hence, only subjects were included as a random factor. The amount of data entering analyses was similar across conditions (i.e., 580, 586, 584, and 607 fixations for the 0-ms, 33-ms, 66-ms, and 99-ms SODs, respectively).

Results and Discussion

Distributions and mean fixation times. Density plots of FFDs and GDs (Figure 5) revealed a pattern comparable to Experiment 1: The distributions of the 66- and 99-ms SODs systematically shifted to the right relative to the adjacent lower SOD, and the increase of mean fixation durations was close to the SOD time steps (Table 4). Similar to Experiment 1, fixation durations in the 0-ms SOD were longer than expected. On average, FFDs were 2 ms longer at the 0-ms compared to the 33-ms SODs; for GDs, the difference (10 ms) was even larger. Accordingly, the 0-ms SOD distribution largely overlapped with the 33-ms SOD condition and revealed shorter fixation durations only in a small range of the fastest saccades (see Figure 5a). Thus, the result of prolonged inspection times after nondelayed versus delayed stimulus onsets was also present in Experiment 2. Although explanations remain tentative (see General Discussion), the replication across two experiments enhances the likelihood that this pattern is reliable. As in Experiment 1, the 0-ms SOD condition caused an underestimation of the slopes for fixation times across onset delays (FFD: 0.61; GD: 0.53). With the 0-ms SOD excluded, the slopes in the nonzero SODs were much steeper (FFD: 0.92; GD: 0.94).

LMM results. We scrutinized fixation durations including SODs, initial landing position, log frequency, and word length as LMM predictors (Table 5). Increases in fixation durations for the 66-ms versus the 33-ms and for the 99-ms versus the 66-ms SODs were significant. In contrast, the comparison of the 33- and 0-ms SODs indicated longer FFDs and GDs for the 0-ms SOD. This result is surprising given an observed FFD difference of only -2 ms (see Table 4), but it reflects an estimated difference of -14 ms (backtransformed from log scale) after statistical control of the other covariates in the LMM (i.e., a suppressor effect). This is also apparent in Figure 4a, which reveals substantially longer FFDs in the 0-ms SOD of Experiment 2 after correcting for influences of other predictors.

In addition to SOD effects, inspection times were again affected by initial landing position. Figure 6a (right panel) shows that GDs were longer at the beginning than in the middle or at the end of words (quadratic trend).

In contrast, FFD increased with fixated letter position (see Figure 6a, left panel). As indicated by the quadratic trend, the increase was stronger at target initial than at central or final positions. That is, fixation durations were shorter near the beginning than near the center or the end of the words, a pattern that is again in line with the IOVP effect (Nuthmann et al., 2005; Nuthmann et al., 2007; Vitu et al., 2001; cf., Experiment 1).[10] The interaction with the contrast between 33- and 0-ms SODs revealed shorter FFDs for 0-ms compared to 33-ms SODs at word initial and final positions, whereas the pattern was reversed for more central landing sites. Moreover, an interaction with the contrast between 33- and 66-ms SODs (FFDs) as well as with the contrast between 66- and 99-ms SODs (FFDs, trend for GDs) indicated that the delay effect was less pronounced at word initial positions.

As in Experiment 1, a main effect of frequency yielded shorter fixation durations for high- than for low-frequency words (cf., Figure 3c−d); none of the interactions of frequency with SOD was significant. Thus, we failed to replicate the stronger frequency effect for the 99-ms SOD observed under the conditions of Experiment 1. Hence, we have no evidence that SOD modulated the processing of lexical information in Experiment 2. At this point, we cannot determine whether the effect was spurious in the first experiment or whether the change to a uniform 0-ms SOD for nontarget words is responsible for its absence in the second experiment.

Word length did not significantly affect fixation durations, neither as a main effect nor in interaction with SOD. Figure 3c suggests, though, that FFDs in the 0-ms SOD condition were numerically longer for short (i.e., four to five letters) than for long (i.e., six to seven letters) words. Thus, consistent with the pattern observed in Experiment 1, word length appears as a candidate to mediate fixation durations when stimuli are unmasked without delay (i.e., 0-ms SOD).

Landing sites and short fixations. Similar to observations in Experiment 1, density plots of the 99- and 66-ms SODs suggested a population of short FFDs that appeared to be separated from longer inspection times (see Figure 5a). Subtracting onset delays from corresponding fixation durations (Figure 5b) makes it clear that the majority of saccades were executed in a range of 150−400 ms after stimulus onset, but that some fixation durations were shorter than 100 ms postonset (FFD: 0.5%, 2.1%, 5.5%, and 7.0%, and GD: 0.0%, 1.6%, 0.7%, and 2.0% of fixations in the 0-, 33-, 66-, and 99-ms SODs, respectively). As in Experiment 1, we tested whether these short fixations originated from viewing positions at the beginning of words and divided FFD distributions into quantile-based landing zones. Indeed, Figure 6b shows that short fixation durations were predominantly observed at landing sites near the beginning of targets. Thus, consistent with Experiment 1, it seems that low-level information related to nonoptimal viewing positions rapidly triggered saccades (cf., Nuthmann et al., 2005; Nuthmann et al., 2007; Vitu et al., 2001; Vitu et al., 2007); from these short fixations, 71% resulted in a refixation on the target word. Further, the drop of saccade rates at about 100 ms after the display change points to an interruption of saccade execution,

[9] As in Experiment 1, the eyes initially landed left from word center (0-ms stimulus-onset delay [SOD]: $M = -0.15$, $SE = 0.02$; 33-ms SOD: $M = -0.15$, $SE = 0.01$; 66-ms SOD: $M = -0.16$, $SE = 0.01$; 99-ms SOD: $M = -0.15$, $SE = 0.01$). Landing positions did not differ between SODs, $F < 1$.

[10] As in Experiment 1, the visual impression of an inverted U-shaped function of the inverted optimal viewing position effect (i.e., decreasing first fixation duration at word final positions) was rather weak. A likely reason is again that word final positions were rarely fixated in Experiment 2. That is, only 18% of first fixations landed in the second half of words.

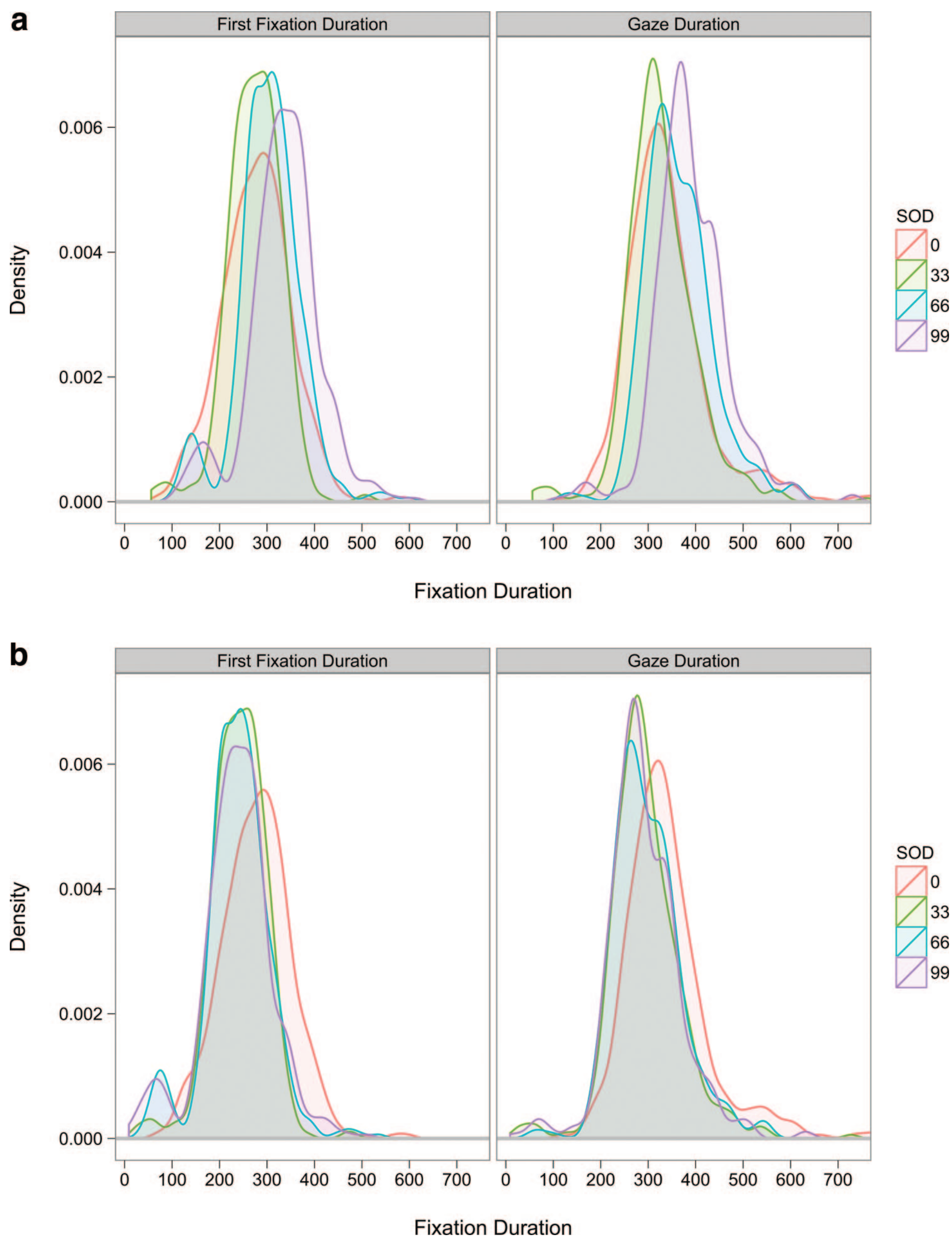


Figure 5. Distributions of first fixation and gaze durations on target words in Experiment 2. Density plots across four stimulus-onset delay conditions (panel a). Density plots of fixation durations relative to target word onset (panel b).

presumably as a consequence of saccadic inhibition (Reingold & Stampe, 1999, 2000, 2004) (see also Footnote 8).

Evidence for direct control? Experiment 2 tested whether onset delays fully translate into increases of fixation durations in the absence of prior temporal preparation. SODs larger than 0 ms were therefore implemented only for target words, while all other words in sentences were immediately[11] unmasked on fixation.

Mean fixation durations indicate that nonzero target SODs were reflected quite accurately in FFDs and GDs (see Table 4). Yet, given the presence of short fixations, slopes are somewhat smaller than 1 (FFD: 0.92; GD: 0.94). When durations of less than 100 ms after stimulus onset are excluded, the slope for FFD increases even slightly above 1 (slope = 1.05; 33-ms SOD: 278 ms; 66-ms SOD: 310 ms; 99-ms SOD: 346 ms) while there is only little change for GD (slope = 0.95; 33-ms SOD: 334 ms; 66-ms SOD: 364 ms; 99-ms SOD: 397 ms). Accordingly, Figure 4a

[11] Note that stimulus unmasking took on average 7 ms after display change initiation.

Table 4
Mean Fixation Durations and Standard Errors on Target Words Together With Difference Scores (Δ) Between SODs and Number of Target Fixations in Experiment 2

	First fixation duration			Gaze duration			*N* fixations	
SOD	*M*	*SE*	Δ	*M*	*SE*	Δ	*M*	*SE*
0	275	5		339	8		1.37	0.04
33	273	6	−2	329	7	−10	1.36	0.04
66	300	6	27	362	6	33	1.41	0.04
99	333	7	33	391	6	29	1.40	0.04

Note. SOD = stimulus-onset delay.

(data from Experiment 2) illustrates that LMM-based estimates of fixation durations linearly increase with approximately unit slope across nonzero SODs.

As in Experiment 1, fixation durations mirrored the experimental manipulation also on nontarget words (see Figure 4b). That is, the 0-ms SOD at pre- and posttarget[12] words yielded comparable FFD and GD, whereas the prolongation due to nonzero SODs clearly showed up on targets. This pattern demonstrates the success of our SOD implementation and supports the validity of our conclusions.

Overall, Experiment 2 results line up with those of Experiment 1. The data suggest that rapid saccades can be triggered by low-level information, independent from lexical processing. The majority of saccades, however, appear to be determined by the time required for processing the fixated word (i.e., word frequency). This is in agreement with a one-to-one translation of stimulus delay into prolongation of fixation duration, and is consistent with direct lexical control of eye movements during reading.

General Discussion

In two experiments, we tested whether SOD during reading translates into an equivalent extension of fixation durations; that is, whether we can demonstrate direct lexical control for eye movements in a boundary paradigm precluding nonfoveal lexical information. The main results can be summarized as follows. First, we observed the expected increase of fixation durations as a one-to-one translation of SODs when we excluded 0-ms SOD and short fixations that were executed within 100 ms after word onset; for the 0-ms SODs, fixation durations were longer than in the 33-ms SOD. Second, analyses of fixation time distributions indicated that the population of rapid saccades was linked to starting locations at the beginning of words. Third, robust frequency effects across all conditions demonstrated that fixation durations depend on word difficulty in addition to the delay of lexical information. In the following, we discuss findings concerning effects of nonzero SODs on fixation times. Then, we turn to the unexpected result relating to the 0-ms SOD.

SOD Effects and Evidence for Direct Control

Previous studies using SODs in reading have generally reported longer fixation durations for increasing delays, but the increase of fixation durations was often smaller than the delay itself (e.g., Rayner & Pollatsek, 1981; Morrison, 1984). We suspected that these experimental designs did not sufficiently rule out the modulation of fixation duration by parafoveal processing of target words. In addition, a number of rapid saccades, presumably due to low-level visual information or preprogramming, may also have veiled a one-to-one translation of SOD to fixation durations (cf., Luke et al., 2012; Nuthmann & Henderson, 2012). Here, we tested this hypothesis (a) by precluding parafoveal preview and (b) by manipulating the delay with which words were displayed once the eye landed on them (i.e., SODs range: 0−99 ms). We reasoned that these delays would be fully reflected in fixation times if no parafoveal information was provided.

In Experiment 1, onset delays were constant for all words in a sentence. In line with previous reports, this resulted in an increase of fixation times. Specifically, later availability of lexical information in the nonzero SODs was quite accurately captured by increases of GD, whereas FFDs were shorter than predicted especially with an SOD of 99 ms. A likely reason for the latter finding is that there was a considerable proportion of rapid saccades in the 99-ms SOD, which deflated fixation time means—and particularly those of FFDs. In fact, excluding fixation durations shorter than 100 ms relative to word onset led to slopes close to 1 for FFDs and even slightly greater than 1 for GDs. Thus, the results were largely compatible with direct control wherein saccade programs are initiated contingent on the presence of the target word. In other words, in the absence of parafoveal processing, delayed starts in lexical processing due to delayed stimulus onsets were compensated for by an equivalent increase in fixation durations.

Theoretical proposals about saccade control distinguish between global and local control of fixation durations (see, e.g., Trukenbrod & Engbert, 2011, for a review). In Experiment 1, all words in a sentence were delayed for the same period. Because the eyes passed on average seven words before they reached the critical target, saccadic control could have adapted to sentence-specific conditions. Hence, the increase in fixation times could also have been due to an adjustment to global temporal settings rather than to local lexical processes. We tested for this possibility in Experiment 2, where all words except for the targets were unmasked with a delay of 0 ms. Thus, nonzero SODs occurred only occasionally and at unpredictable positions (i.e., on target words) so that global temporal preparation to specific delays was impossible (cf., Henderson & Pierce, 2008). Critically, target fixation durations still reflected the onset delays very precisely, that is, slopes of FFDs and GDs across nonzero delays were approximately 1 after excluding rapid saccades that started less than 100 ms after word onset. The results are therefore comparable to those of constant onset delays (Experiment 1), and, again, in the absence of parafoveal processing, they are in line with a one-to-one translation of word onset into fixation duration.

The pattern of delay-induced prolongations of fixation durations is summarized in Figure 4b, illustrating the course of FFDs and GDs over five successive words. The plot shows that constant SODs in Experiment 1 yielded increasing fixation times on all

[12] The visual impression of stimulus-onset delay−specific differences on the posttarget word in Experiment 2 (see Figure 4b) was not significant in linear mixed models on FFD ($|t|$s < 0.96, ps $> .10$) or GD ($|t|$s < 1.66, ps $\geq .10$).

Table 5
LMM Effects of SOD, Landing Position (Linear and Quadratic Trend), Logarithmic Frequency, and Word Length in Experiment 2

	First fixation duration				Gaze duration			
	Estimate	*SE*	*t*	*p*	Estimate	*SE*	*t*	*p*
Fixed effects								
(Intercept)	5.73	0.02	266.69	0.000	5.79	0.02	312.54	0.000
SOD (33–0)	−0.05	0.02	−2.16	0.034	−0.05	0.02	−2.35	0.020
SOD (66–33)	0.12	0.02	5.58	0.000	0.13	0.02	6.61	0.000
SOD (99–66)	0.10	0.02	4.65	0.000	0.10	0.02	4.89	0.000
LandPos	−0.01	0.05	−0.32	0.737	0.05	0.04	1.09	0.291
LandPos^2	−1.34	0.12	−10.87	0.000	0.92	0.12	7.88	0.000
logFrequency	−0.01	0.00	−2.66	0.005	−0.01	0.00	−3.51	0.000
Length (short−long)	0.02	0.01	1.43	0.147	−0.01	0.01	−1.24	0.215
SOD (33–0) × LandPos	0.07	0.12	0.54	0.575	−0.03	0.12	−0.29	0.797
SOD (66–33) × LandPos	−0.26	0.13	−2.01	0.041	−0.04	0.12	−0.37	0.707
SOD (99–66) × LandPos	−0.20	0.13	−1.57	0.117	−0.05	0.12	−0.43	0.670
SOD (33–0) × LandPos^2	0.96	0.33	2.87	0.005	−0.02	0.32	−0.05	0.966
SOD (66–33) × LandPos^2	−0.92	0.34	−2.68	0.008	−0.31	0.32	−0.95	0.334
SOD (99–66) × LandPos^2	−0.75	0.35	−2.13	0.031	−0.64	0.33	−1.92	0.057
SOD (33–0) × logFrequency	0.01	0.01	1.03	0.305	−0.01	0.01	−0.74	0.448
SOD (66–33) × logFrequency	−0.01	0.01	−1.00	0.310	0.01	0.01	0.45	0.647
SOD (99–66) × logFrequency	−0.01	0.01	−1.02	0.305	0.00	0.01	−0.10	0.920
SOD (33–0) × Length (short−long)	−0.05	0.03	−1.64	0.110	0.00	0.03	0.11	0.908
SOD (66–33) × Length (short−long)	−0.03	0.03	−0.92	0.355	−0.03	0.03	−0.81	0.416
SOD (99–66) × Length (short−long)	0.04	0.03	1.22	0.217	0.01	0.03	0.47	0.646
Random effects	*SD*	HPD95 lower	HPD95 upper		*SD*	HPD95 lower	HPD95 upper	
Subjects	0.113	0.077	0.126		0.096	0.066	0.113	
Residual	0.224	0.217	0.232		0.212	0.206	0.220	

Note. Only subjects are specified as random factor. LMM = linear mixed models; SOD = stimulus-onset delay; LandPos = landing position; HPD95 = 95% highest posterior density interval.

words. In contrast, nonzero delays in Experiment 2 triggered sudden increases of fixation durations only on targets, while they were very similar across all conditions on target-preceding words (i.e., 0-ms SOD). Fixation durations therefore largely line up with delay manipulations, and they reveal a remarkable correspondence between the experiments.

Obviously, our results are limited in generalizability, because display changes may trigger other processes that affect fixation durations. One likely candidate, for example, is saccadic inhibition, that is, the cancellation of current saccadic programs due to visual onsets, which has been shown to cause systematic shifts in fixation durations (Reingold & Stampe, 1999, 2000, 2004). In fact, the distributions of fixation durations revealed a drop of saccade rates at about 100 ms after word onset in the current experiments.

Especially at long SODs, this translated into a bimodality of the distributions, which showed that a considerable proportion of fixations were terminated within the first 100 ms after the stimulus was unmasked (see also Footnote 8). Such rapid saccades are most likely too fast to be initiated by lexical processing (cf., Becker & Jürgens, 1979; Martínez et al., 1999). In fact, closer examination of the short inspection times showed that they predominantly resulted from fixations at nonoptimal viewing positions at the beginning of words. This is compatible with the proposal that fixations landing at unintended viewing positions due to oculomotor error (i.e., away from the intended word center) can trigger corrective saccades (Nuthmann et al., 2005; Nuthmann et al., 2007; see also Engbert et al., 2005; Reichle et al., 2009). Such corrective saccades can essentially be initiated without delay under the assumption of continuous saccade monitoring, wherein an efference copy of the motor command to the eye muscles informs about discrepancies between the intended and the actually executed saccade program (cf., Carpenter, 2000). As another contributor, the perceptual economy hypothesis suggests that fixation durations are shorter at locations that are expected to provide little lexical information, such as at word edges. Estimates of processing efficiency can be rapidly made on the basis of low-level visual information, for example, the distance of interword spaces from the fixation position (Vitu et al., 2001; Vitu et al., 2007); in fact, visual masks did not cover interword spaces, they preserved information about word boundaries. Finally, it is possible that rapid saccades were preprogrammed prior to target fixation. This preprogramming cannot be the result of parafoveal lexical preprocessing (Morrison, 1984), but it is in accord with mechanisms of autonomous saccade timing (see below, e.g., Engbert & Kliegl, 2001; Nuthmann & Henderson, 2012; Trukenbrod & Engbert, 2011). Yet, this account does not explain the relation of rapid saccades and fixation position, and it therefore may only partly contribute to the observed pattern.

In sum, our results indicate that during reading with gaze-contingent display changes, a number of saccades are detached from lexical processing; those are triggered either directly on the basis of low-level visual information or indirectly by an autonomous saccade timer. On the other hand, the data provide convincing evidence that the majority of fixations feature a one-to-one mapping of word onset and lexical information (i.e., frequency, see below) into fixation duration, supporting a perspective of direct lexical control (Reingold et al., 2012).

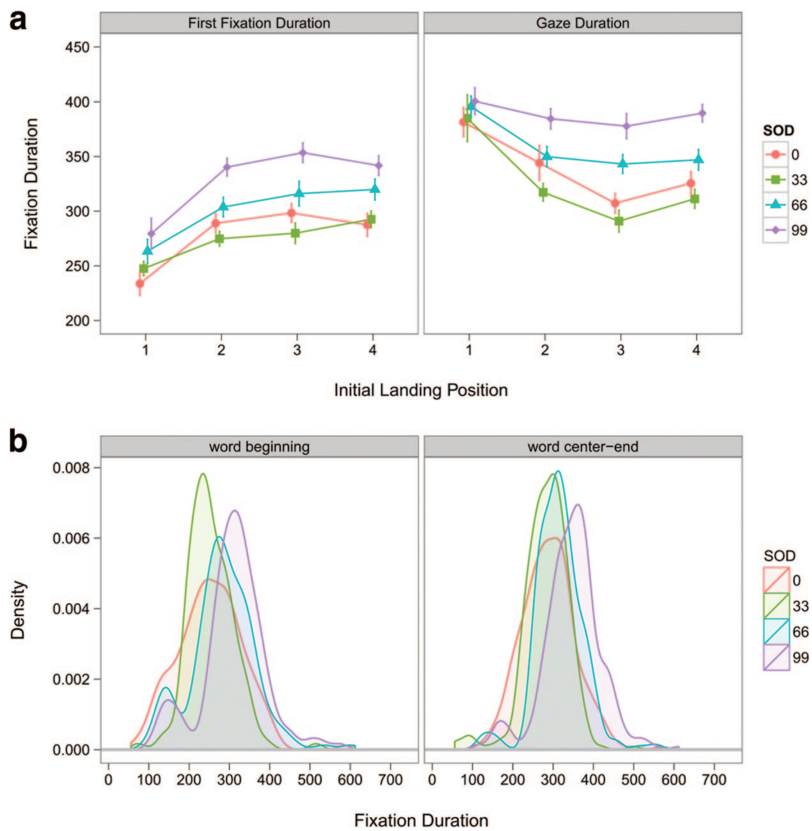


Figure 6. Effects of initial landing position on target words in Experiment 2. First fixation and gaze durations across initial landing positions and stimulus-onset delays. Data points reflect quantiles of the overall landing site distribution. Error bars reflect standard errors (panel a). Density plots of first fixation durations landing close to the word beginning (first quarter) or center-to-end region (second through fourth quarters) (panel b).

Implications for Models of Oculomotor Control

Similar results have been reported in recent SOD experiments on scene viewing and paragraph reading, which also revealed bimodal distributions of inspection times (Henderson & Pierce, 2008; Henderson & Smith, 2009; Luke et al., 2012; Nuthmann & Henderson, 2012). Modal values of fixation durations longer than the masking interval increased with SODs with a slope of 1, whereas fixation times shorter than the SOD were unaffected by the delay. The data were simulated with CRISP, a model for fixation durations in scene viewing, which combines autonomous saccade timing with direct oculomotor control (Nuthmann et al., 2010). Specifically, CRISP assumes that (a) programming of a new saccade is initiated when a discrete-stage random walk reaches a threshold, and (b) saccade programming consists of a labile and a nonlabile stage. Visual−cognitive processing difficulties can directly prolong a fixation because they can inhibit the random walk and may cancel a labile saccade program. However, depending on the saccade programming stage, visual−cognitive influences may sometimes come in too late, especially when the current fixation is short, because the saccade program has already started during the previous fixation. With these principles, the model was able to account for fixation time distributions and captured SOD-related effects in paragraph reading (Nuthmann & Henderson, 2012; see also Luke et al., 2012).

Clearly, the generalizability of these results to our data cannot be taken for granted, because the paragraph reading studies implemented full-screen masks that occurred only occasionally and did not preclude parafoveal preview. In contrast, our one-word moving window on single-line sentences restricted bottom-up lexical processing to the foveal word and featured comparably subtle display changes. Given the similarity of the results, though, the CRISP simulations inform about possible implications of our data for current models of oculomotor control in reading.

For instance, the SWIFT model (which shares core principles with CRISP) assumes that saccades are initiated by an autonomous random timer that draws durations from a gamma distribution (SWIFT 2, Engbert et al., 2005). In a more recent version, the timer has also been implemented as a discrete random walk, together with a dynamic attentional span that is modulated by foveal load (SWIFT 3, Schad & Engbert, 2012; see also Trukenbrod & Engbert, 2011). Critically, random timing in SWIFT models can be directly inhibited by foveal processing difficulties, causing a prolongation of fixation durations. In addition, and in line with the principle of reafference, saccades from unintended viewing positions can be rapidly initiated to correct for oculomotor errors. Thus, SWIFT incorporates principles of both indirect (e.g., random timer) and direct control (e.g., foveal inhibition).

Another class of models has a stricter focus on direct control. For instance, the E-Z Reader model (Reichle et al., 1998; Reichle et al., 2006; Reichle et al., 2009) assumes that fixation durations are under immediate control of current lexical processing. After an early familiarity check of the fixated word (Stage L1), a saccade program to the next word is initiated, while the current word is further fixated and processed up to a level of lexical completion (Stage L2). Most often, L2 finishes earlier than the saccade program, resulting in a covert attention shift to the next word, which is then preprocessed (if parafoveally available). The critical point is that lexical processing is a prerequisite for saccade initiation. Yet, the model also incorporates the assumption that refixations can be rapidly triggered when the eyes land away from intended viewing positions (i.e., reafference).

Apparently, both architectures implement mechanisms of direct lexical control that can account for a one-to-one mapping of SODs into fixation durations. Further, they feature principles that permit the execution of rapid saccades from nonoptimal viewing positions (i.e., nonlexical direct control; see also Reingold et al., 2012). Qualitatively, it therefore seems that both classes of models are compatible with our data. Future comparisons of the different implementations of direct and indirect control may show whether one of them can capture the data more reliably on a quantitative level.

Word Frequency and Lexical Processing

We also obtained a robust effect of word frequency with shorter fixation durations for high- than for low-frequency words in both FFDs and GDs. This is in line with other studies that have provided evidence for direct lexical control in reading. For instance, Staub, White, Drieghe, Hollway, and Rayner (2010) fitted ex-Gaussian distributions to FFDs and GDs. All distributions shifted to the right for low- compared to high-frequency words, suggesting that lexical processing directly affects early (FFD) and later (GD) measures of eye movements.

Robust frequency effects have also been shown in the disappearing text paradigm in which words were removed or masked 60 ms after fixation onset (Liversedge et al., 2004; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Rayner, Liversedge, White, & Vergilino-Perez, 2003). This indicates that lexical information extracted from the first 60 ms of foveal vision has a strong effect on oculomotor control. Of note, reading is relatively unimpaired when only the fixated word disappears, but the simultaneous removal of the word to the right of the fixation substantially distorts reading (Rayner, Liversedge, & White, 2006).

Similarly, Reingold et al. (2012) recently showed that direct lexical control of eye movements critically depends on parafoveal preprocessing. Specifically, ex-Gaussian and survival analyses revealed word frequency effects in FFD distributions from 145 ms onward, when target words were visible during the fixation on the previous word. In contrast, when targets were masked prior to fixation, the frequency effect was reduced in mean fixation durations and emerged only after 256 ms, that is, when 60% of FFDs were already terminated.

The frequency effects in our data were relatively robust, although parafoveal preview was always precluded. A likely reason is that our setting generally slowed down reading, granting more time for frequency to affect fixation durations. In fact, fixation durations in the 0-ms SOD were about 50 ms longer than in unconstrained reading (see also Reingold et al., 2012, in which preview was prevented only on the target word). This slowing of reading speed roughly corresponds to the size of the preview benefit effect, that is, the temporal advantage of fixation durations after correct compared to incorrect parafoveal preview (Rayner, 2009). As a related issue, it may also point to a modified reading strategy relying exclusively on foveal and ignoring parafoveal information.

The frequency effect in GD of Experiment 1 was modulated by SOD: The frequency effect was significantly stronger for the 99-ms than the 66-ms SOD (which did not differ from the shorter SODs). It is possible that the interaction indicates that processing of high-frequency words benefits from long waiting periods. A potential reason is that long SODs afforded processing of the present and the next word length, which could be retrieved from mask size. Hence, although we have effectively eliminated bottom-up lexical processing until after the delay, visual information from the mask may have biased readers to predict the upcoming word from the prior context.[13] Although the predictability of our target words was generally low, the natural correlation of predictability and frequency (e.g., Dambacher & Kliegl, 2007) may have caused a larger benefit of such predictions for high- than for low-frequency words. Such predictive inferences are likely enhanced for the long SODs in Experiment 1, in which constant delays granted additional time prior to obtaining useful bottom-up lexical information on every word. In Experiment 2, in contrast, a top-down based strategy may have been less useful because nonzero delays occurred only occasionally on target words. Consequently, the interaction of frequency and SOD was not significant. The exact reasons for the different patterns between the experiments remain unknown at this stage. It is also possible that the interaction did not replicate because it was a spurious result in Experiment 1 or because, for example, the difference in unmasking times between target and nontarget words in Experiment 2 caused disruptions, which eliminated this effect.

Zero Versus Nonzero SODs?

Finally, we address a puzzling issue: the 0-ms SOD yielded longer fixation durations than the 33-ms SOD. This result is roughly in agreement with Inhoff et al. (2005), who did not find a significant increase between 0 and 70 ms SODs. Hohenstein et al. (2010) discussed this result as an inconsistency with the increase they observed between 33 and 66 ms SODs. The present set of results reconciles this difference: apparently, there is another process contributing during 0-ms SODs.

One potential factor is that display changes due to the unmasking of words are visible in nonzero SODs, but occur during a saccade at a 0-ms SOD and, therefore, are mostly not perceived. According to current evidence, saccadic inhibition predominantly depends on the visibility of display changes (see above; Reingold & Stampe, 2004). In a series of experiments designed to assess the detection of display changes during reading, Slattery et al. (2011) found evidence of saccadic inhibition only in conditions in which the display change was delayed. Such a difference between immediate and delayed display changes may cause a qualitative difference between the nonzero and 0-ms SODs. Thus, the 33-ms SOD may indeed serve as a more appropriate reference condition for onset delays in the present experiments.

[13] We thank an anonymous reviewer for pointing this out.

Further influences may arise from saccadic suppression, that is, the phenomenon that uptake of visual information is strongly reduced during a saccade. Even after offset of reading saccades, it takes about 30 ms for sensitivity to fully recover (Ishida & Ikeda, 1989; Matin, 1974). Accordingly, visual processing in the 0- and 33-ms SODs may start in a similar time range, which would explain comparable fixation durations.

Indeed, Vaughan (1982; see also Vaughan & Graefe, 1977) obtained essentially equal fixation durations in a 0-ms SOD compared to a 30-ms or a 60-ms SOD condition in a visual search task. They suggested that foreperiods, during which stimuli are masked, can serve as a warning signal that facilitates the response to an upcoming stimulus and may even accelerate oculomotor latencies. In fact, visual warning signals substantially reduce saccadic response times (Ross & Ross, 1981). Accordingly, the pattern of "too long" fixation durations in our 0-ms SOD condition (no foveal mask) may actually reflect "too short" fixation durations in the nonzero delay conditions, where brief visual masks served as warning signals.

Figure 3a and c indicated that the pattern of long FFDs in the 0-ms SOD was particularly pronounced for short words in both experiments. Indeed, the inverse main effect of length in Experiment 1 was no longer reliable when the 0-ms SOD was excluded. This suggests that stimulus size affected fixation durations especially when words were unmasked without delay. We can currently only speculate why, but the pattern may be important for follow-up research addressing the replicability and causes of this effect.

Conclusions

The main message of the present experiments is that (with the exception of early triggered saccades from nonoptimal landing positions), autonomous saccade generation can be completely disabled with nonzero stimulus onset delays. Previous research had suggested a mixture of autonomous and direct control, but none of these studies had eliminated parafoveal lexical processing to the same degree as the present experiments. Thus, we can engineer a one-to-one translation of SOD into fixation duration when parafoveal information processing is entirely prevented. This will offer new windows of experimental control on an understanding of time lines of saccade initiation and how it interfaces with lexical processing during natural reading.

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Received January 29, 2012
Revision received November 29, 2012
Accepted December 13, 2012 ■