Saccadic and smooth-pursuit eye movements during reading of drifting texts

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Reading is a complex visuomotor behavior characterized by an alternation of fixations and saccadic eye movements. Despite the widespread use of drifting texts in various settings, very little is known about eye movements under these conditions. Here we investigated oculomotor behavior during reading of texts which were drifting horizontally or vertically at different speeds. Consistent with previous reports, drifting texts were read by an alternation of smooth-pursuit and saccadic eye movements. Detailed analysis revealed several interactions between smooth pursuit and saccades. On one side, the gain of smooth pursuit was increased after the execution of a saccade. On the other side, the peak velocity of saccades was reduced for the horizontally drifting text, in which saccades and pursuit were executed in opposite directions. In addition, we show that well-known findings from the reading of static texts extend to drifting text, such as the preferred viewing location, the inverted optimal viewing position, and the correlation between saccade amplitude and subsequent pursuit/fixation duration. In general, individual eye-movement parameters such as saccade amplitude and fixation/pursuit durations were correlated across self-paced reading of static text and time-constrained reading of static and drifting texts. These results show that findings from basic oculomotor research also apply to the reading of drifting texts. Similarly, basic reading principles apply to the reading of static and drifting texts in a similar way. This exemplifies the reading of drifting text as a visuomotor behavior which is influenced by low-level eye-movement control as well as by cognitive and linguistic processing.

Introduction

Reading is a complex visuomotor behavior in which eye movements exploit the strength and compensate for the limitations of the human visual system (for a review, see Rayner, 1998). Due to the decline in spatial acuity and crowding in the retinal periphery (for a review, see Strasburger, Rentschler, & Juttner, 2011), the text is scanned by alternations of fixations and saccadic eye movements. Information uptake mainly happens during fixation at the fovea, and saccades move the fovea from one position in the text to the next. Several oculomotor parameters, like saccade amplitudes and fixation durations, are driven partially by the cognitive processing of the text (for a review, see Engbert, Nuthmann, Richter, & Kliegl, 2005).

Humans are also capable of reading drifting text, which is often used in situations where display space is limited, like mobile devices, advertisements, or information panels (Kang & Muter, 1989). There have been several applied studies investigating reading speed and word comprehension for different presentation methods of drifting texts (Kang & Muter, 1989; Laarni, 2002; Bowers, Woods, & Peli, 2004; So & Chan, 2008). Moreover, drifting text has been suggested as a tool to improve reading in people with dyslexia (Krischer, Coenen, Heckner, Hoeppner, & Meissen, 1994) or visual impairments (Fine & Peli, 1995; Harland, Legge, & Luebker, 1998; Bowers et al., 2004). Compared to these applied and clinical studies, there is very little oculomotor research on the reading of drifting texts. As in the case of static texts, eye movements in reading drifting texts have to adapt to the properties of the visual system. Presumably because visual acuity declines at retinal velocities above 2.5°/s (Westheimer & McKee, 1975), the fixations during normal reading are replaced by smooth-pursuit eye movements when the text is drifting (Latin script: Buettner, Krischer, & Meissen, 1985; Öquist & Lundin, 2007; Chinese script:

Sun & Feng, 1999). These studies merely reported the occurrence of smooth eye movements, without investigating oculomotor behavior in more detail. However, a lot of findings on saccadic and smooth-pursuit eye movements that were obtained using artificial laboratory stimuli might also transfer to the prime example for saccade-pursuit interactions: the reading of drifting texts.

Since fixations are replaced by smooth-pursuit eye movements, the reading of drifting text requires a close coordination of saccadic and smooth-pursuit eye movements. Traditionally, saccades and smooth pursuit have been considered to act on completely distinct input signals: Saccades compensate for retinal position errors and smooth pursuit compensates for retinal slip (Rashbass, 1961). However, in the last decade, converging evidence has supported the notion that the two types of eye movements are closely coupled. On the neurophysiological level, it has been shown that saccadic and smooth-pursuit eye movements are controlled by largely overlapping neural networks (for a review, see Krauzlis, 2004). Oculomotor research (for a review, see Orban de Xivry & Lefevre, 2007) has gathered evidence for velocity input to saccade control, affecting saccade amplitudes (Gellman & Carl, 1991; de Brouwer, Missal, & Lefevre, 2001) and saccade dynamics (de Brouwer, Missal, Barnes, & Lefevre, 2002; Guan, Eggert, Bayer, & Buttner, 2005). Conversely, studies have also provided evidence for position input to smooth-pursuit control (Segraves & Goldberg, 1994; Blohm, Missal, & Lefevre, 2005). In fact, both systems interact to optimize eye-movement behavior (Orban de Xivry, Bennett, Lefevre, & Barnes, 2006).

Saccadic and smooth-pursuit eye movements do not just cooperate to minimize errors in retinal position and velocity; they also affect each other directly. For instance, when smooth-pursuit initiation is interrupted by saccades, postsaccadic pursuit gain is enhanced compared to presaccadic gain (Lisberger, 1998). So far, this postsaccadic pursuit enhancement has been only tested in a situation where a single drifting target is tracked explicitly. Hence it is unknown whether it also occurs in more complex situations, like the reading of drifting texts. Moreover, the execution of a saccade can determine or even override the target selection of smooth pursuit (Gardner & Lisberger, 2001; Spering, Montagnini, & Gegenfurtner, 2008). In the other direction, the dynamics of saccades are affected by the execution of smooth pursuit (de Brouwer et al., 2002).

For an oculomotor study on the reading of drifting texts, the motion direction of the text is of great importance for three reasons. First, applied studies have reported a superior reading rate for horizontally oriented text drifting vertically compared to drifting horizontally (Laarni, 2002). Second, eye movements are not completely isotropic; for instance, the gain of smooth pursuit is typically higher for horizontal than for vertical motion (Collewijn & Tamminga, 1984; Rottach et al., 1996). Third, the requirements for the cooperation of saccadic and smooth-pursuit eye movements are completely different for horizontal and vertical motion. In left-to-right languages, the horizontally drifting text is typically drifting against the reading direction, that is, leftward. In this case, smooth-pursuit and saccadic eye movements have to be executed in opposite directions, very similar to the pattern of slow and fast phases in optokinetic nystagmus. For vertically drifting text, in contrast, the direction of smooth pursuit and the main component of saccades are orthogonal. In the former case, a tight coupling of saccades and smooth pursuit is required, whereas in the latter case, saccade and smooth pursuit could act fairly independent of each other.

In this study we investigated how saccadic and smooth-pursuit eye movements interact in the reading of drifting texts. To this end, we asked observers to read static as well as horizontally and vertically drifting texts at different speeds. The line length and presentation rate of the static-text conditions were adjusted to impose similar reading speeds.

Methods

Observers

Two groups of 12 students from the Justus-Liebig University of Giessen volunteered to participate in the study (horizontally drifting text group: 11 females, one male, mean age = 22; vertically drifting text group: 12 females, mean age = 23.6). All of the participants reported having normal or corrected-to-normal vision and being native speakers of German. All observers provided written informed consent in agreement with the Declaration of Helsinki. Methods and procedures were approved by the local ethics committee LEK FB06 at Giessen University (proposal number 2009-0008).

Stimuli

Texts

A corpus of 84 short texts taken from articles in the science section of the German online magazine *Spiegel Online* was used in both experiments. The texts had to be meaningful when read in isolation (usually we chose the opening sentences of magazine articles). The average length of the texts was 59 words (range = 33–91). Each text was associated with a question related to
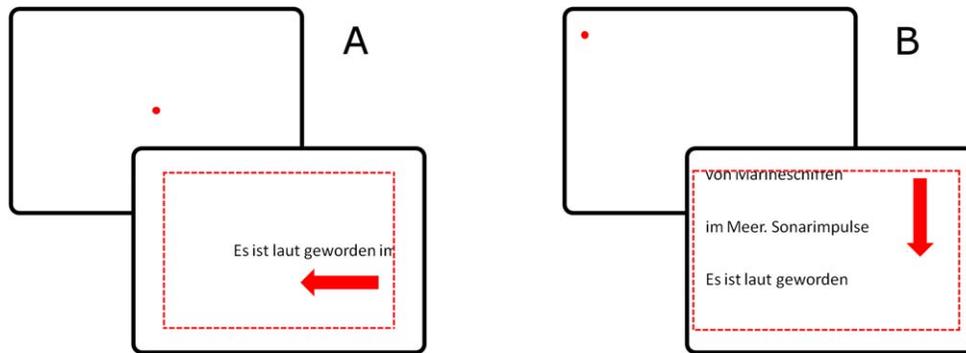
Figure 1. Display and procedure. (A) Horizontally drifting text. (B) Vertically drifting text. For both drift axes, observers fixated on the red dot and pressed a key to start reading. The red arrows and the red dashed rectangles (not present in the experimental display) indicate the direction of text motion and the window where the text was visible, respectively.

its content, which required a true/false response. For the pretest session, observers read one full article with 275 words from the same magazine section. To avoid mindless reading, observers had to answer four questions about the full article afterwards. This pretest session was used to measure the natural reading behavior in a fairly standard presentation condition.

Display

The sentences were displayed on a 21-in. Sony Trinitron F520 CRT monitor (Sony Corporation, Tokyo, Japan), viewed from a distance of 47 cm. The monitor frame rate was 100 Hz and the pixel resolution was 1280 × 1024.

The text was displayed in black on a white background. We used the Arial font, at size 20, corresponding to a character height of 42.3 arcmin.

Stimulus presentation was controlled using Matlab (MathWorks, Inc., Natick, MA) and the PsychToolbox (Brainard, 1997; Pelli, 1997).

Eye-movement recording

Eye movements were recorded using an Eyelink 1000 (SR Research, Kanata, ON, Canada) tower-mount eye tracker controlled by the Eyelink toolbox (Cornelissen, Peters, & Palmer, 2002). The position of the right eye was sampled at 1000 Hz. The spatial resolution was 0.01°. Saccadic events were detected using the Eyelink online parser, which uses a velocity threshold of 22°/s and an acceleration threshold of $3,800°/s^2$. The average velocity in the last 40 ms is added to the velocity threshold, which allows saccade detection even during ongoing smooth-pursuit eye movements.

Procedure

Two experiments were conducted, involving either horizontally or vertically drifting text. In both cases, we also tested a condition where static text was read in a comparable display and with a comparable presentation rate. In general, a trial involved the presentation of one text, followed by the question to which the observers responded by pressing one of two keys.

Horizontally drifting text: At the beginning of each trial, the observers fixated on a dot in the center of the screen (Figure 1A). After a key press, the initial words of the text appeared 7° right of the fixation point and started drifting towards the left at a speed of either 10.57°/s or 14.09°/s (3 and 4 pixels per refresh frame, respectively). The visible text was contained within a window of 31° centered in the screen.

In the static-text condition, the text was segmented in lines which were as long as possible while still fitting in the viewing window. Observers fixated on the left of the text window and the lines were presented sequentially, aligned on the left side of the viewing window. The presentation time of each line was scaled to the line length (44 ms per character).

The three text speeds (0, 10.57 and 14.09 °/s) were tested in three separate blocks of 25 trials. At the beginning of each block of trials, the observer was informed whether the text would move slowly, move fast, or be static. The first trial of each block was considered practice, and the corresponding data were not analyzed.

Vertically drifting text: At the beginning of the trial, the observers fixated on a dot located 15.51° left of and 10.57° above or below the center of the screen, corresponding to downward- and upward-drifting text, respectively (Figure 1B). After a key press, the first line of the text appeared next to the fixation point and drifted at a speed of 3.52°/s or 7.05°/s (1 or 2 pixels per screen-refresh frame). The subsequent lines appeared in the same position, one after the other, at a distance of 5.56°. The lines were visible within a window whose vertical size was 21.14°; thus a maximum of three or four lines were visible on the screen at the same time. In order to approximately equate reading-speed demands

	Beginning/end of trial	Backward saccade	Outside of screen center	Too-short intersaccadic interval	Epoch contaminated by blinks	Outlier sample along track	Total
Horizontally drifting text	20.0 ± 0.3%	11.8 ± 1.1%	24.2 ± 4%	0.9 ± 0.3%	2.2 ± 0.6%	6 ± 0.5%	65.3 ± 3.1%
Vertically drifting text	15.2 ± 0.2%	32.3 ± 1.7%	6 ± 0.2%	1.4 ± 0.2%	1 ± 0.3%	9.3 ± 0.4%	65.5 ± 1.1%

Table 1. Percentages of saccadic epochs discarded from the analysis based on different selection criteria.

when the text speed increased, we imposed a maximum number of characters per line of 38 when the text speed was 3.52°/s and 18 when the text speed was 7.05°/s.

In the case of the static text, four lines were present on the screen at the same time. We tested two conditions with static text, where the maximum line length was matched to the one we used in the two text speeds (38 and 18 characters). In order to make clear that our experimental design is fully factorial, in the remainder of this article we refer to the static-text conditions with short and long lines by the labels which define the slow and fast speeds of the drifting text associated with the same line length. Again, the four lines remained on the screen for a time equal to 44 ms times the total number of characters.

Each of the six combinations of text speed (3.52°/s or 7.05°/s) and motion direction (upward, static, and downward) was tested in a separate block of 14 trials. At the beginning of each block of trials, the observer was informed about the speed and direction of the test motion. The first trial of each block was considered practice, and the corresponding data were not analyzed.

Pretest: In the case of the pretest, the text was presented on two pages, the first containing 18 lines and the second containing 16 lines. Reading was self-paced: Observers pressed the space bar on the keyboard in order to switch from the first page to the second and in order to signal that they had finished reading.

Data analysis

Event selection

In both the horizontal- and vertical-reading experiments, we tried to isolate the steady-state reading saccades. To this end, we discarded the data from both the first and last 2 s of recording from each trial. Second, in order to identify perisaccadic pursuit tracks not contaminated by multiple saccadic events, we discarded all saccadic events where another saccade was observed in the 50 ms preceding the start of the event and in the 100 ms following the start of the event. Third, in the case of the horizontally drifting text, we decided to discard the saccadic events whose horizontal starting and landing positions were within 3.52° of the left and right borders of the text-viewing window. These borders constituted a screen-fixed landmark even

though the text was drifting and in these regions only parts of the words would be visible. In a similar approach, when the text drifted vertically we discarded the saccadic events whose vertical starting and landing position were within 1.76° of the upper and lower border of the text-viewing window. Finally, we only selected saccades going from left to right, thus removing saccades leading to refixations and line jumps (in the vertically drifting text experiment). In the case of the pretest data, we only considered the fixation and saccadic events whose positions were to the right of the immediately preceding one and left of the next one, thus excluding events directly following or preceding regressions or line jumps.

Artifact removal

After selecting the saccadic events, we isolated the eye tracks of the relevant coordinate (x for the horizontally drifting text and y for the vertically drifting text), ranging from 50 ms before to 100 ms after the beginning of each saccade. Each track was baseline-corrected by subtracting the average position in the first 50 ms. For each observer and experimental-design cell, we computed the mean and standard deviation of the baseline-corrected position tracks in 16 equally spaced samples (i.e., every 10 ms). The tracks whose position value differed from the mean by more than two standard deviations in any of the 16 samples were discarded from the analysis together with the corresponding saccade events. The percentages of epochs which were discarded based on the different criteria are indicated in Table 1.

Statistical analysis

We analyzed the extracted eye-movement parameters with repeated-measure ANOVAs with factors for text motion and text speed. Differences between individual factor levels were assessed with t tests, and p values were adjusted with the Bonferroni correction for multiple comparisons.

Comprehension task

To avoid mindless reading, participants had to answer one question after each text, with four questions after the self-paced reading in the pretest. This
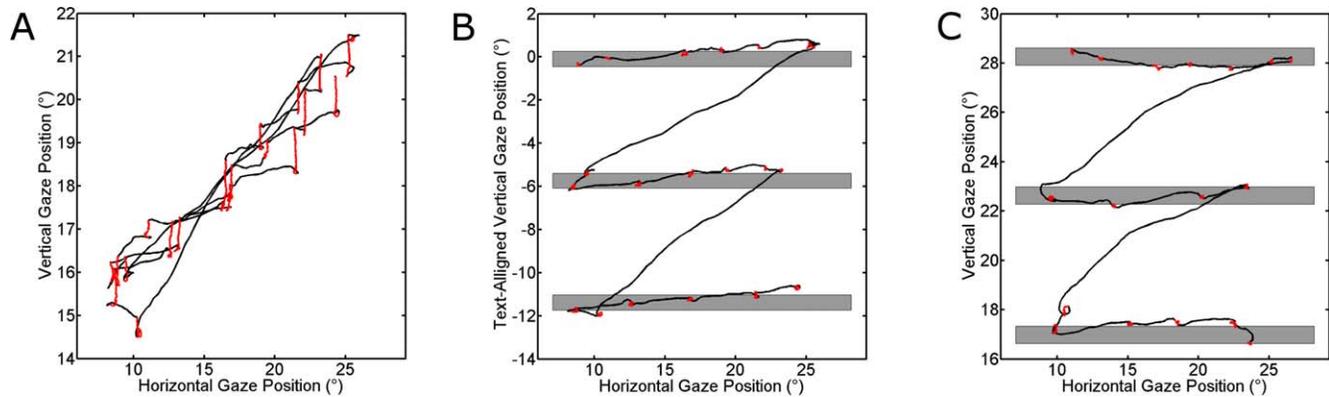
Figure 2. Exemplary eye-movement traces. (A) Raw eye-position measurements from one observer reading vertically drifting text (direction upward, speed 3.52°/s). (B) Same eye-movement data as in (A), but this time referenced to the position of the drifting text. (C) Example of eye movements while the same observer read a static text. Red identifies the smooth-pursuit episodes in (A) and (B) and fixation episodes in (C), whereas saccadic eye movements are marked in black. Notice that smooth-pursuit episodes appear as elongated lines along the vertical axis (i.e., the text-drift direction) in (A) and are approximately reduced to a point in (B). The gray rectangles mark the vertical position of the text lines. The origin of the reference frame is the lower left corner of the screen in (A) and (C), whereas the vertical position in (B) is referenced to the initial position of the text line which was read first.

comprehension task involved true/false questions with an equal probability of each response; thus the chance-level performance would have been 50%. The participants who read the text drifting horizontally answered 72.8% of the comprehension questions correctly, on average. Their accuracy did not change between the three text speeds (static, 10.57°/s, or 14.09°/s), $F(2, 22) = 0.906$, $p = 0.418$, $\eta^2 = 0.076$. In the case of the vertically drifting text, the answers were correct in 70.4% of the cases. The observers' accuracy was influenced by neither the direction nor the speed of the text motion [main effect of direction: $F(2, 22) = 0.968$, $p = 0.396$, $\eta^2 = 0.08$; main effect of speed: $F(1, 11) = 0.957$, $p = 0.349$, $\eta^2 = 0.08$; direction × speed interaction: $F(2, 22) = 1.644$, $p = 0.216$, $\eta^2 = 0.13$].

Results

Fixation/smooth-pursuit episode duration

The observers read the drifting text through episodes of smooth-pursuit tracking. This behavior largely compensates for text drift, and the resulting text-referenced eye movements are similar to those observed during the reading of static text (see Figure 2 for an example from the vertically drifting text experiment).

The duration of those smooth-pursuit episodes, along with the durations of the fixations during the reading of static text in the horizontally drifting text experiment, are shown in Figure 3A. A one-way repeated-measure ANOVA with text speed (static, 10.57°/s, or 14.09°/s) as the factor indicated that the

duration was greater for the smooth-pursuit episodes in the reading of drifting text as compared to the fixations in the reading of static text. The main effect of text speed was significant, $F(2, 22) = 29.627$, $p < 0.001$, $\eta^2 = 0.73$. Furthermore, post hoc comparisons indicate that fixations executed during the reading of the static text were shorter than both the smooth-pursuit episodes when the text moved at 10.57°/s, $t(11) = 7.525$, $p < 0.001$, and when the text moved at 14.09°/s, $t(11) = 5.025$, $p < 0.001$. The smooth-pursuit episodes did not have a significantly different duration in the two text speeds, $t(11) = 2.261$, $p = 0.135$.

The duration of smooth-pursuit episodes and fixations in the vertically drifting text experiment are shown in Figure 3B. The condition with the higher text speed was associated with a shorter duration of the fixations when the text moved upward and with shorter fixations when the text was static. A two-way repeated-measure ANOVA with direction and speed of text motion as factors revealed a significant effect of text speed, $F(1, 11) = 28.934$, $p < 0.001$, $\eta^2 = 0.72$, and a significant two-way interaction, $F(2, 22) = 7.488$, $p < 0.003$, $\eta^2 = 0.41$; the main effect of the direction of text motion was not significant, $F(2, 22) = 1.104$, $p = 0.349$, $\eta^2 = 0.09$. The effect of text speed was significant when the text moved upward, $t(11) = 8.882$, $p < 0.001$, and when the text was static, $t(11) = 3.844$, $p < 0.008$, but was not significant when the text was drifting downward, $t(11) = 2.7$, $p = 0.067$. The fact that fixations were shorter in the 7.05°/s condition when observers read static text indicates that this effect is more likely to be due to the fact that the text was presented in shorter lines rather than to the motion of the text.

The duration of the fixations and smooth-pursuit episodes in the horizontally drifting text (Table 2) and
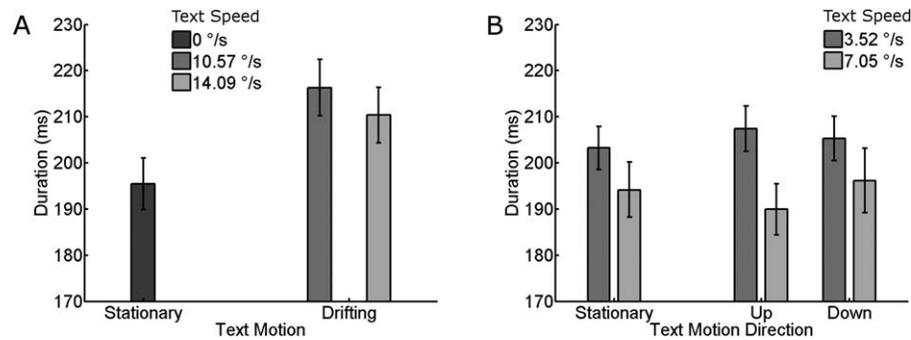
Figure 3. Durations of fixations (in the static-text condition) and of smooth-pursuit episodes (in drifting-text conditions). (A) Horizontally drifting text. The fixations in the static-text condition were shorter than the smooth-pursuit episodes in reading drifting text. (B) Vertically drifting text. The durations were reduced in the condition with a text speed of 7.05°/s—that is, when the lines were shorter—both when the text moved upward and when it was static. Error bars in both parts of the figure are standard errors of the mean.

the vertically drifting text (Table 3) was strongly positively correlated to the duration of the fixations that each observer produced in the self-paced reading pretest experiment. This indicates that individual differences in reading style were not completely erased by the reading pace imposed by our experimental manipulations.

Transsaccadic smooth-pursuit gain modulation

In Figure 4A and B is presented the evolution of smooth-pursuit gain through the time course of a selected subset of smooth-pursuit episodes. In order to construct the plots, we selected episodes from the horizontally and vertically drifting text experiments whose durations ranged between 170 and 190 ms and realigned all the corresponding pursuit gain tracks to a fixed duration of 180 ms. A further Gaussian filtering with 4.7 ms full width at half height was applied to the tracks to reduce aliasing. For each observer, we pooled episodes from all text speeds, and for the vertically drifting text experiment we pooled episodes also from the upward and downward directions of text motion, and subsequently we averaged the tracks across observers. In the case of the horizontally drifting text data, a postsaccadic enhancement of pursuit gain is evident as soon as the gaze reaccelerates at the end of

the saccade (saccade and pursuit are in opposite directions), and after around 50 ms the pursuit gain decreases below 1. A similar pattern of decreasing pursuit gain along the episode time course is evident in the case of the vertically drifting text, although, given that the saccade and smooth-pursuit directions are substantially orthogonal, the pursuit gain is already near 1 at saccade onset.

In order to investigate the modulation of smooth-pursuit gain in a larger number of episodes without having to deal with largely different durations, we also investigated the evolution of smooth pursuit, aligning the tracks separately on saccade onset and offset (Figure 4C through H). The postsaccadic enhancement of smooth-pursuit gain 30–50 ms after saccade offset is still present when all episode durations are considered, and in all cases the gain of the smooth pursuit seems to increase across saccades.

In order to test the effect of the execution of a saccade on the ongoing smooth pursuit, we compared the gain of the smooth pursuit (i.e., the ratio of pursuit speed to text speed) in a time window preceding the onset of the saccade (50–30 ms before onset) and in a time window well after the conclusion of the saccadic events (30–50 ms after offset). In the case of the

Comparison condition	r	p value (Bonferroni corrected)
Static	0.877	0.001
10.57°/s	0.892	0.001
14.09°/s	0.823	0.003

Table 2. Correlation of episode (fixation and smooth-pursuit) durations in the pretest self-paced reading and in each condition of the horizontally drifting text experiment. All three correlations are positive and significant.

Comparison condition	r	p value (Bonferroni corrected)
Upward, 3.52°/s	0.878	0.001
Static, 3.52°/s	0.896	0.001
Downward, 3.52°/s	0.902	0.001
Upward, 7.05°/s	0.856	0.002
Static, 7.05°/s	0.867	0.001
Downward, 7.05°/s	0.824	0.006

Table 3. Correlation of episode (fixation and smooth-pursuit) durations in the pretest self-paced reading and in each condition of the vertically drifting text experiment. All six correlations are positive and significant.
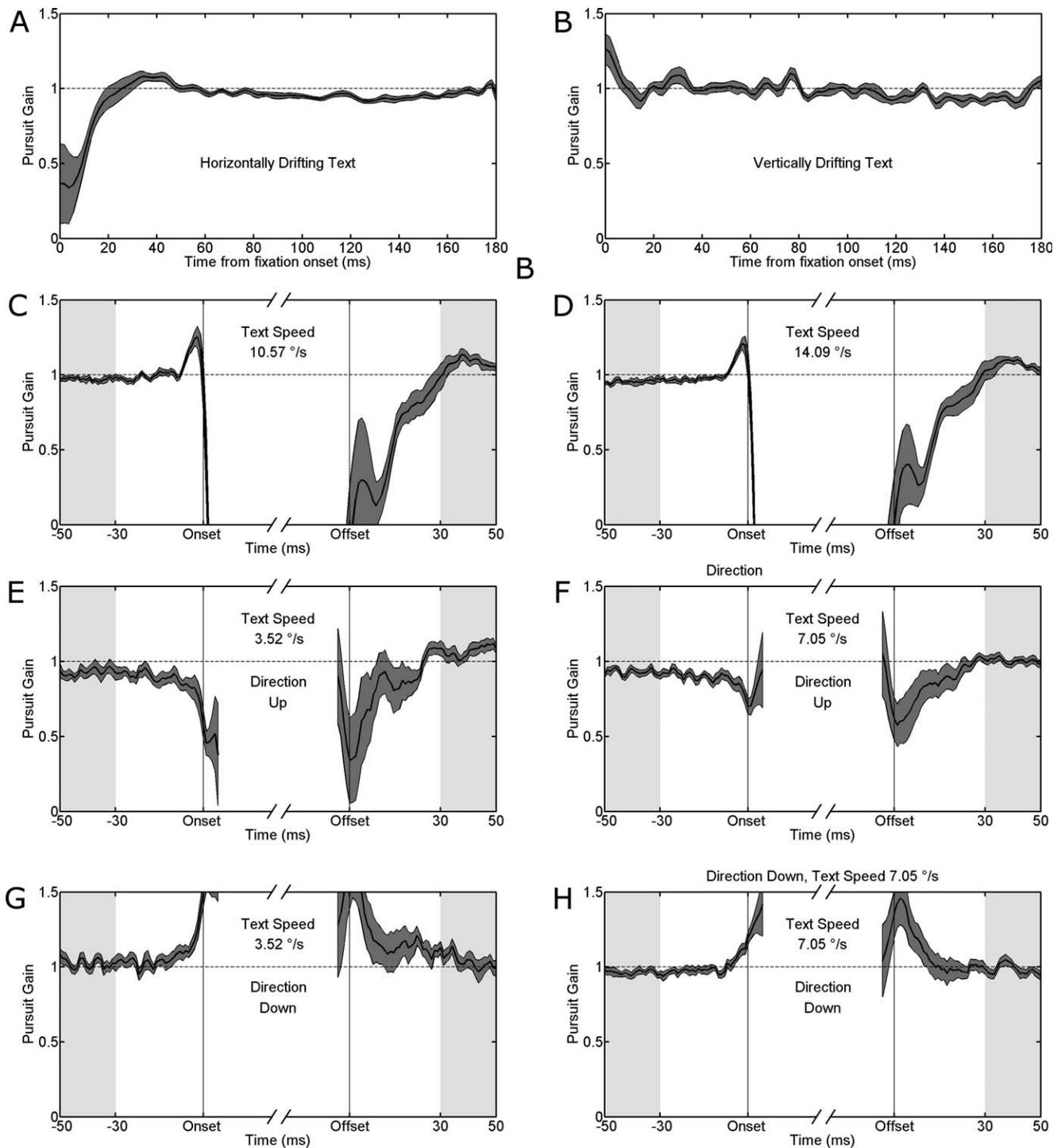
Figure 4. Evolution of smooth-pursuit gain throughout the fixation time course (A and B) and across saccades (C through H). (A and B) Tracks with slightly different durations have been remapped to a fixed duration of 180 ms. Data have been pooled over all text speeds and text-motion directions. (C through H) Perisaccadic modulation of pursuit gain in the horizontally (C and D) and vertically (E through H) drifting text experiments. Presaccadic gain tracks were aligned on saccade onset, whereas postsaccadic tracks were aligned on saccade offset. Light-gray areas delimit the time intervals where pre- and postsaccadic pursuit gain was sampled in order to construct Figure 5. Gray filled areas represent ±1 standard error of the mean.
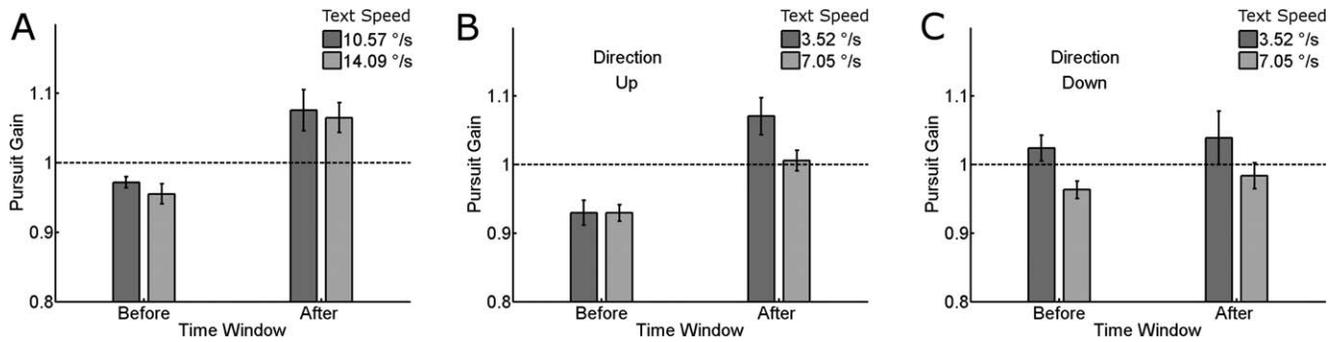
Figure 5. Pursuit gain. Pursuit gain was computed in two time windows (before: 50–30 ms before saccade onset; after: 30–50 ms after saccade onset). (A) Horizontally drifting text. Pursuit gain increased after saccade execution and was higher for the lower speed. (B) Upward-drifting text. (C) Downward-drifting text. (B and C) Similar to horizontally drifting text, the gain of the smooth pursuit increased after saccade execution and was larger for the lower text speed. All error bars are standard errors of the mean.

horizontally drifting text (Figure 5A), results were analyzed by means of a two-way repeated-measure ANOVA with time window (before vs. after) and text speed (10.57°/s vs. 14.09°/s) as factors. The smooth-pursuit gain increased after the saccade [main effect of time window: $F(1, 11) = 39.383$, $p < 0.001$, $\eta^2 = 0.78$], whereas the speed at which the text drifted had no influence [main effect of text speed: $F(1, 11) = 1.166$, $p = 0.303$, $\eta^2 = 0.10$; text speed × time window interaction: $F(1, 11) = 0.075$, $p = 0.789$, $\eta^2 = 0.01$].
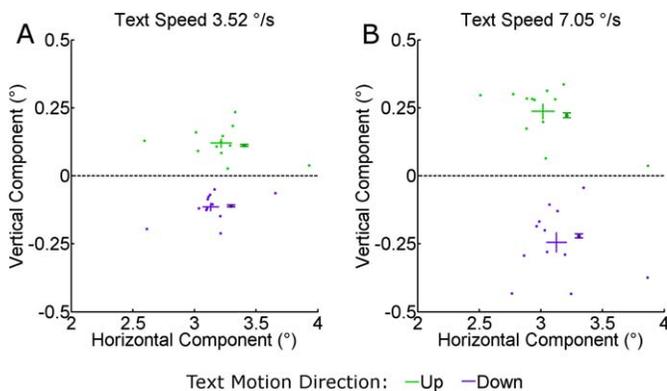

Figure 6. Average vertical and horizontal components of saccadic eye movements executed while observers read text drifting vertically at the two speeds (A and B, respectively). Each dot represents an observer's average; the crosses represent the mean and standard error of the mean of the components. The error bars on the right of the crosses represent the average vertical displacement of the text which occurred during the saccade ±1 standard error of the mean. Saccadic eye movements with amplitudes between 1° and 5° were selected for this plot. The vertical component of saccades executed while reading static text was subtracted from the component observed while observers read drifting text. The vertical component of the saccades largely overlaps with the text motion, indicating that the tracking of the text is integrated in the programming of saccades.

In the case of the vertically drifting text, results were analyzed by means of a three-way repeated-measure ANOVA with time window (before vs. after), text speed (3.52°/s vs. 14.09°/s), and text direction (upward vs. downward) as factors. The pattern of results was partially similar to the one observed in the case of the horizontally drifting text (Figure 5B and C). The gain of the smooth pursuit increased after saccade execution [main effect of time window: $F(1, 11) = 67.165$, $p < 0.001$, $\eta^2 = 0.85$] and was higher when the text speed was lower as compared to the higher text speed [main effect of text speed: $F(1, 11) = 30.020$, $p < 0.001$, $\eta^2 = 0.73$]. Furthermore, the increase in pursuit gain after the saccade was larger for the slower text speed [text speed × time window interaction: $F(1, 11) = 8.742$, $p < 0.013$, $\eta^2 = 0.44$]. None of the effects and interactions involving direction of text motion was significant [main effect of text-motion direction: $F(1, 11) = 0.546$, $p = 0.475$, $\eta^2 = 0.04$; time window × text-motion direction interaction: $F(1, 11) = 3.580$, $p = 0.085$, $\eta^2 = 0.09$; text speed × text-motion direction interaction: $F(1, 11) = 1.469$, $p = 0.250$, $\eta^2 = 0.11$; three-way interaction: $F(1, 11) = 3.468$, $p = 0.089$, $\eta^2 = 0.23$]. The postsaccadic increase in pursuit gain was mainly evident when the text drifted downwards, $t(11) = 5.048$, $p < 0.001$, and failed to reach significance when the text drifted upwards, $t(11) = 1.564$, $p = 0.292$.

Saccade pursuit component

In the case when the text was moving vertically, the question arises as to whether the programming and execution of the mainly horizontally oriented reading saccades took into account the concomitant orthogonal drifting of the text. The average vertical and horizontal components of saccades executed while reading verti-cally drifting text are represented in Figure 6. The data seem to indicate that saccades target the position where
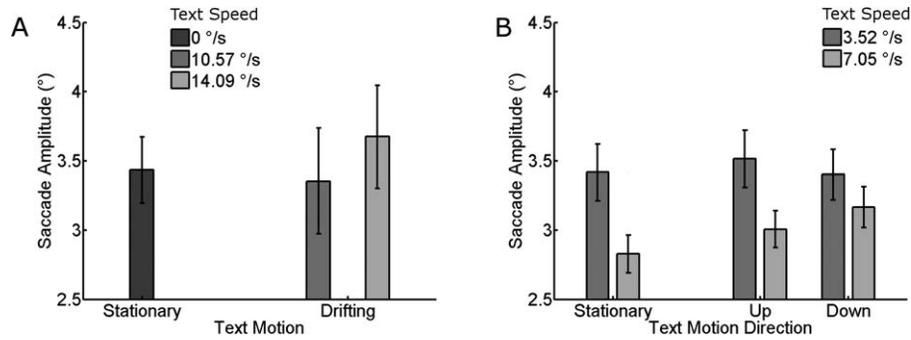
Figure 7. Saccade amplitudes. (A) Horizontally drifting text. Saccade amplitude did not differ between different text-motion speeds. (B) Vertically drifting text. Saccade amplitude was reduced in the condition with a text speed of 7.05°/s (i.e., with shorter text lines) when the text was stationary or moved upwards. All error bars are standard errors of the mean.

the text arrives at the end of the saccade, rather than being horizontal.

In order to construct the plot in Figure 6, we first isolated forward reading saccades (i.e., excluded backward line jumps) with an amplitude between 1° and 5°. We noticed that for most observers, the saccades executed while reading static text had a quite sizable vertical component, which we attribute to a slight calibration misalignment. Thus, as a second step in the analysis, for each observer and text speed we linearly regressed the vertical amplitude of the saccades executed while reading static text on their horizontal amplitude. The regression parameters were then used to predict the amount of artifactual vertical component for the saccades executed while reading vertically drifting text, as a function of their horizontal component. Furthermore, for each saccade executed while observers read the drifting text, we computed the amount of vertical drift that the text covered between the start and the end of the saccade, that is, the vertical component that the saccade should have in order to perfectly target the future position of the text.

In order to evaluate the results statistically, we performed a three-way repeated-measure ANOVA on the vertical components (taking as positive a displacement coherent with the direction of text motion) with prediction (observed vs. predicted), direction of text motion (upward vs. downward), and text speed (3.52°/s vs. 7.05°/s) as factors. This analysis evidenced a highly significant effect of text speed, $F(1, 11) = 144.716$, $p <$ 0.001, $\eta^2 = 0.92$, whereas all the remaining main effects and interactions were not significant [main effect of prediction: $F(1, 11) = 0.620$, $p = 0.447$, $\eta^2 = 0.05$; main effect of text-motion direction: $F(1, 11) = 0.003$, $p = 0.960$, $\eta^2 = 0.01$; prediction × text speed interaction: $F(1, 11) = 0.543$, $p = 0.476$, $\eta^2 = 0.04$; prediction × text-motion direction interaction: $F(1, 11) = 0.005$, $p = 0.944$, $\eta^2 = 0.01$; text speed × text-motion direction interaction: $F(1, 11) = 0.099$, $p = 0.759$, $\eta^2 = 0.01$; three-way interaction: $F(1, 11) = 0.108$, $p = 0.748$, $\eta^2 = 0.01$]. The ANOVA results confirm that the vertical compo-

nent of saccades scales with text-motion speed, so as to cover the vertical displacement of the text which occurs while the saccade is executed.

Saccade amplitude

Average saccadic amplitude in the horizontally drifting text experiment is shown in Figure 7A. A one-way repeated-measure ANOVA with text speed (static, 10.57°/s, or 14.09°/s) as a factor evidenced that saccadic amplitude did not change as a function of text speed, $F(2, 22) = 2.100$, $p = 0.146$, $\eta^2 = 0.16$. Notice that if saccadic programming fully took into account the motion of the text, thus simply summing to smooth pursuit, the horizontal saccades should be shorter by the space which is covered by the text during the saccade. This does not seem to be the case, and indeed the data in Figure 11A seem to indicate that saccades land farther to the right within a word when the text drifts towards the left as compared to when it is static.

Average saccadic amplitude in the vertically drifting text experiment is shown in Figure 7B. Saccadic amplitudes were analyzed with a two-way repeated-measure ANOVA using text speed (3.52°/s vs. 7.05°/s) and text direction (upward, downward, or static) as factors.

The amplitude of the saccades decreased in the condition of the higher text speed, $F(1, 11) = 33.294$, $p < 0.001$, $\eta^2 = 0.75$. Furthermore, the amplitude of saccades was affected by the direction of motion, $F(2, 22) = 14.161$, $p < 0.001$, $\eta^2 = 0.56$, and the two factors showed a significant interaction, $F(2, 22) = 15.301$, $p < 0.001$, $\eta^2 = 0.58$. The interaction was due to the fact that the effect of text speed was significant in the conditions where the text was drifting upwards, $t(11) = 5.572$, $p < 0.001$, and where the text was static, $t(11) = 7.077$, $p < 0.001$, but not in the condition where the text was drifting downwards, $t(11) = 2.783$, $p = 0.053$. Notice that the fact that text speed had an effect on saccade amplitude when the text was static strongly suggests

Comparison condition	r	p value (Bonferroni corrected)
Static	0.913	0.001
10.57°/s	0.929	0.001
14.09°/s	0.898	0.001

Table 4. Correlation of observers' saccadic-amplitude averages in the pretest self-paced reading and in each condition of the horizontally drifting text experiment. All three correlations are positive and significant.

that this effect can be interpreted as our observers executing shorter saccades when the text lines contained fewer characters rather than as an effect of text motion per se.

Tables 4 and 5 represent the coefficients and associated p values for the correlations between saccadic-amplitude averages in the pretest, where reading was paced, and in the different conditions of the two experiments. Similar to the case of the fixation duration, all correlations were significantly positive, indicating that the individual differences in reading style were preserved and suggesting that the reading behavior was not completely altered by the display properties.

Relationship of saccade amplitude and fixation/pursuit duration

We investigated both the correlation between the amplitude of a saccade and the duration of the next fixation and the correlation of the duration of a fixation with the amplitude of the next saccade. After removing outlier events (saccades smaller than 0.5° and larger than 7° and fixation/smooth-pursuit episodes shorter than 100 ms and longer than 500 ms), we computed the linear-regression fit from saccade amplitude to fixation/smooth-pursuit episode.

Previous saccade

The average parameters of the linear regression for the relationship between fixation duration and the amplitude of the previous saccade in the horizontally drifting text experiment are represented in Figure 8A and C. In general, all slopes were positive, $t(11) = 4.065$, $p < 0.002$, and were not influenced by the text speed, as evidenced by a one-way repeated-measure ANOVA, $F(2, 22) = 1.668$, $p = 0.212$, $\eta^2 = 0.13$. The same analysis applied on the intercept values yielded instead a significant effect of text speed, $F(2, 22) = 9.1$, $p < 0.001$, $\eta^2 = 0.45$. Post hoc comparisons indicate that the intercept values when the text was drifting at 10.57°/s were larger than when it was static, $t(11) = 3.263$, $p < 0.023$, and than when it was drifting at 14.09°/s, $t(11) =$

Comparison condition	r	p value (Bonferroni corrected)
Upward, 3.52°/s	0.894	0.001
Static, 3.52°/s	0.741	0.035
Downward, 3.52°/s	0.891	0.001
Upward, 7.05°/s	0.813	0.008
Static, 7.05°/s	0.895	0.001
Downward, 7.05°/s	0.76	0.025

Table 5. Correlation of observers' saccadic-amplitude averages in the pretest self-paced reading and in each condition of the vertically drifting text experiment. All six correlations are positive and significant.

3.879, $p < 0.008$; the intercept values did not differ between the condition where the text was static and where it was drifting at 14.09°/s.

The average parameters of the linear regression for the vertically drifting text experiment are represented in Figure 8B and D. Once again, the slopes were in general positive, $t(11) = 10.990$, $p < 0.001$, and were not significantly influenced by any of our experimental manipulations, as evidenced by a two-way repeated-measure ANOVA with text speed and text-motion direction as factors [main effect of text-motion direction: $F(2, 22) = 1.425$, $p = 0.262$, $\eta^2 = 0.11$; main effect of text speed: $F(1, 11) = 1.976$, $p = 0.189$, $\eta^2 = 0.15$; text speed × text-motion direction interaction: $F(2, 22) = 1.201$, $p = 0.32$, $\eta^2 = 0.10$].

The same analysis applied to the intercept values instead evidenced a significant effect of text speed, $F(1, 11) = 11.218$, $p < 0.006$, $\eta^2 = 0.5$, whereas the main effect of text-motion direction, $F(2, 22) = 1.775$, $p = 0.193$, $\eta^2 = 0.14$, and the two-way interaction, $F(2, 22) = 1.946$, $p = 0.167$, $\eta^2 = 0.15$, were not significant. This result can thus be interpreted as a general shortening of the fixation/pursuit episode duration when the line length was reduced.

Next saccade

The average parameters of the linear regression for the relationship between fixation duration and the amplitude of the next saccade in the horizontally drifting text experiment are represented in Figure 9A and C. Contrary to what we observed in the case of the previous saccade, the relationship between the duration of a fixation and the amplitude of the next saccade is not straightforward. As evidenced by a one-way repeated-measure ANOVA, the slope of the linear regression depended on text motion $F(2, 22) = 5.775$, $p < 0.009$, $\eta^2 = 0.34$. Specifically, in none of the three text-motion conditions did the slope values differ significantly from 0 [static: $t(11) = 1.101$, $p = 0.88$; 10.57°/s: $t(11) = 0.971$, $p = 1$; 14.09°/s: $t(11) = 2.796$, $p = 0.052$]; however, the slopes proved to be higher when
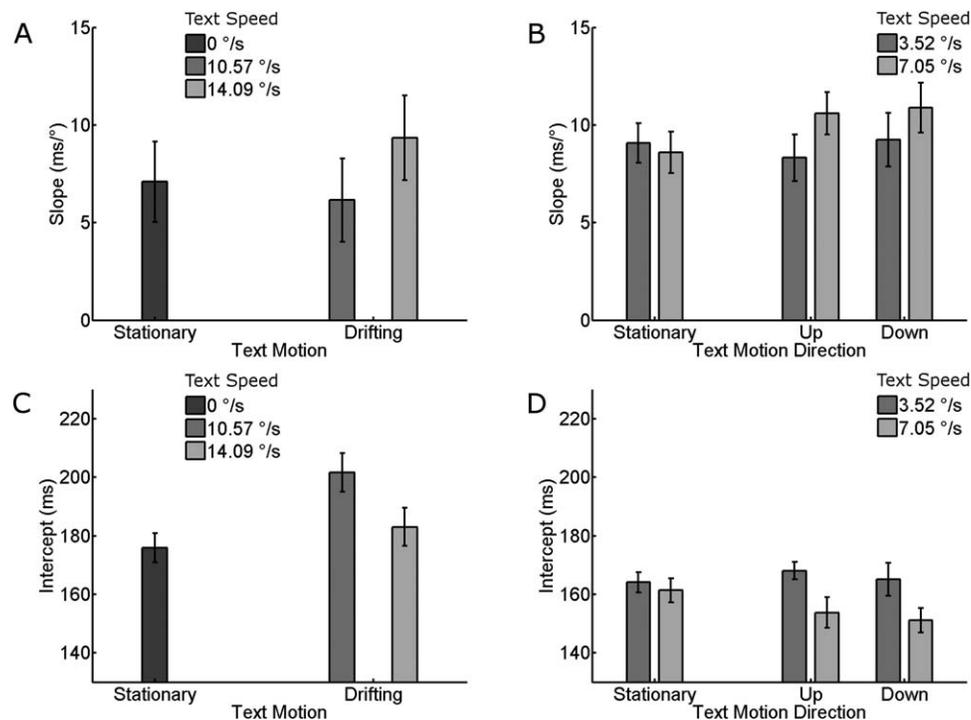
Figure 8. Correlation between fixation/smooth-pursuit duration and previous saccade amplitude. Average slope (A and B) and intercept (C and D) values from the linear regression of fixation/smooth-pursuit duration as a function of the previous saccade amplitude. (A and C) Horizontally drifting text. All slope values were positive and did not differ between experimental conditions. Intercept values were higher when the text speed was 10.57°/s as compared to the other two conditions of text-motion speed. (B and D) Vertically drifting text. All slope values were positive and did not differ between experimental conditions. Intercept values were higher when the text speed was 7.05°/s as compared to 3.52°/s. All error bars are standard errors of the mean.

the text drifted at 14.09°/s as compared to when the text was static, $t(11) = 3.057$, $p < 0.032$. The slope values when the text drifted at 10.57°/s did not differ from those observed when the text was static, $t(11) = 1.754$, $p = 0.321$, and when the text drifted at 14.09°/s, $t(11) = 1.970$, $p = 0.223$. Conversely, the effect of text motion on the intercept values was not significant, $F(2, 22) = 1.900$, $p = 0.173$, $\eta^2 = 0.14$.

The average parameters of the linear regression for the vertically drifting text experiment are represented in Figure 9B and D. In no case were the slopes significantly different from 0; nonetheless, it appears that the values were more positive in the case when the text lines were longer. A two-way repeated-measure ANOVA with text speed and text-motion direction as factors evidenced a significant main effect of text speed, $F(1, 11) = 4.873$, $p < 0.049$, $\eta^2 = 0.31$, whereas the main effect of text-motion direction, $F(2, 22) = 0.152$, $p = 0.86$, $\eta^2 = 0.01$, and the text speed × text-motion direction interaction, $F(2, 22) = 0.541$, $p = 0.589$, $\eta^2 = 0.05$, were not significant.

The same analysis applied to the intercept values again evidenced a significant effect of text speed, $F(1, 11) = 9.518$, $p < 0.010$, $\eta^2 = 0.46$, whereas the main effect of text-motion direction, $F(2, 22) = 1.391$, $p = 0.270$, $\eta^2 = 0.11$, and the two-way interaction, $F(2, 22) =$

0.553, $p = 0.583$, $\eta^2 = 0.05$, were not significant. This result can thus be interpreted as a general shortening of the saccades when the line length was shortened.

Saccade peak velocity

The relationship between peak velocity and amplitude is one of the most stereotypical characteristics of saccades, (Bahill, Clark, & Stark, 1975). The shorter lines associated with the higher text speeds induced a reduction of saccade amplitude. To circumvent this problem while comparing saccade peak velocity between conditions, we decided to further select the saccadic events and generate saccade-amplitude-equalized sub-samples. To this end, for each observer in each experiment, we isolated the horizontal amplitude component of each saccade and calculated a target amplitude value from the average of the observer's median amplitude in each experimental-design cell. The average across observers of the saccade-amplitude target values was 4° in the horizontally drifting text experiment and 3.34° in the vertically drifting text experiment. For each observer and design cell, we subsequently selected 30 events from the amplitude-sorted original pool, starting from the one with the amplitude nearest to the
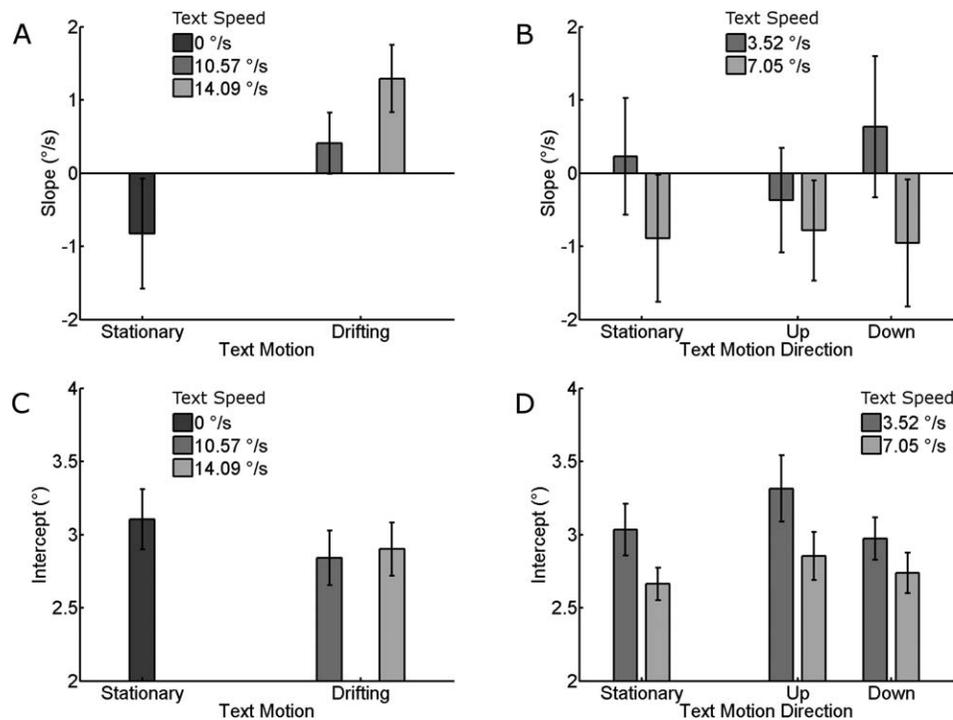
Figure 9. Correlation between fixation/smooth-pursuit duration and following saccade amplitude. Average slope (A and B) and intercept (C and D) values from the linear regression of fixation/smooth-pursuit duration as a function of the previous saccade amplitude. (A and C) Horizontally drifting text. Slope values were higher when the text drifted at 14.09°/s compared to when it was static. (B and D) Vertically drifting text. Slope values were higher when the text speed was 3.52°/s, that is, when the lines were longer. Intercept values were lower when text speed was 7.05°/s, indicating that shorter saccades tended to be executed when the text lines were shorter. All error bars are standard errors of the mean.

target value and subsequently adding the following ones based on their rank, in order to get an overall mean amplitude as close as possible to the target one. This procedure was largely effective, and the actual average amplitude of saccades varied very little between conditions for each observer. The average subject-wise standard deviation of subsample mean amplitude was 0.004° in the horizontally drifting text experiment and 0.003° in the vertically drifting text experiment.

Average saccadic peak velocity in the horizontally drifting text experiment is shown in Figure 10A. A one-way repeated-measure ANOVA with text speed (static, 10.57°/s, or 14.09°/s) as a factor indicated that saccadic peak velocity was influenced by text speed, despite the amplitude equalization, $F(2, 22) = 19.368$, $p < 0.001$, $\eta^2 = 0.64$. In particular, post hoc comparisons indicate that the peak velocity of saccades executed while reading the static text was higher than the peak velocity
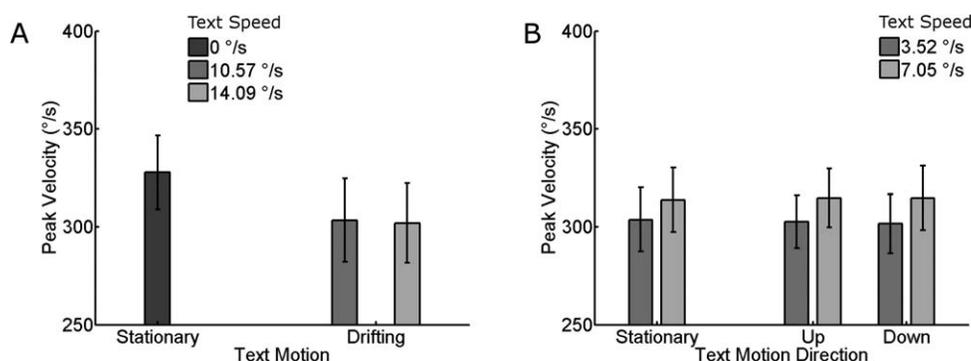

Figure 10. Saccade peak velocity. (A) Horizontally drifting text. Saccade peak velocity was lower when the text was drifting as compared to when the text was static. (B) Vertically drifting text. Saccade peak velocity was lower when the text was presented in longer lines, that is, in the 3.52°/s condition. In both parts of the figure, data from subsamples with equal saccadic amplitude for each observer are shown. Error bars are standard errors of the mean.
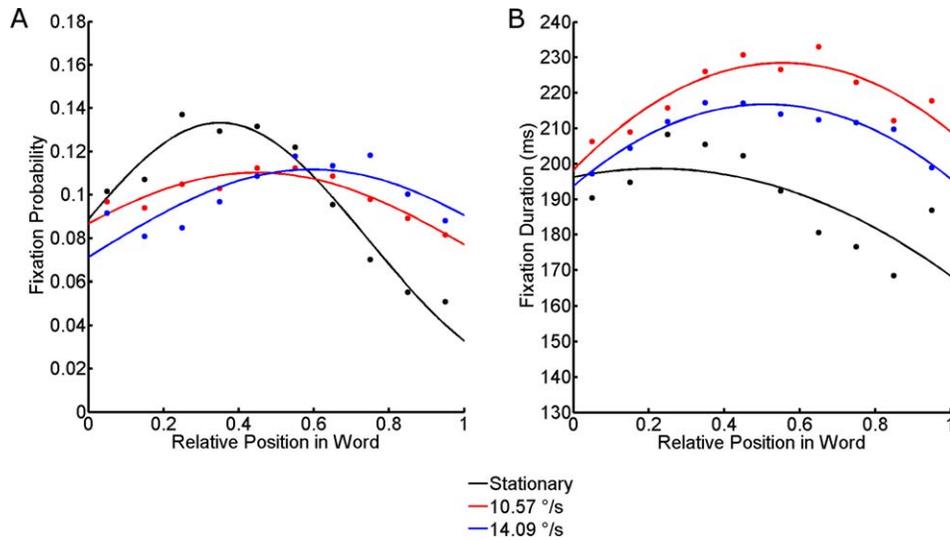
Figure 11. Preferred viewing location (A) and inverted optimal viewing position (B) in the horizontally drifting text experiment. Data are aggregated for words whose length ranged between 5 and 10 characters. The solid lines are Gaussian model fits in (A) and three-parameter IOVP model fits in (B). The PVL and IOVP curves were shifted to the right when the text was moving.

of saccades executed both when the text moved at $10.57°/s$, $t(11) = 46.128$, $p < 0.001$, and when the text moved at $14.09°/s$, $t(11) = 5.138$, $p < 0.001$. Since pursuit and saccades go in opposite directions, a reduction of saccade peak velocity is compatible with a summation of saccade and pursuit motor commands (de Brouwer et al., 2002).

Average saccadic peak velocity in the vertically drifting text experiment is shown in Figure 10B. The corresponding data were analyzed by means of a repeated-measure two-way ANOVA with text-motion direction (upward, static, or downward) and text speed ($3.52°/s$ vs. $7.05°/s$) as factors. Evidently, saccadic peak velocity was increased in the $7.05°/s$ speed condition [main effect of text speed: $F(1, 11) = 22.733$, $p < 0.001$, $\eta^2 = 0.67$]. However, no significant effect of text-motion direction, $F(2, 22) = 0.013$, $p = 0.989$, $\eta^2 = 0.01$, or, crucially, the interaction, $F(2, 22) = 0.203$, $p = 0.818$, $\eta^2 = 0.02$, emerged—once again suggesting that this effect is driven by the length of the text lines rather than by the text motion. Since saccades and text motion are orthogonal to each other, one would not expect large changes of saccade peak velocity.

Preferred viewing location (PVL) and inverted optimal viewing position (IOVP)

Two of the most widespread findings related to the saccadic targeting of words in reading are the PVL (Rayner, 1979) and the IOVP (Vitu, McConkie, Kerr, & O'Regan, 2001). The PVL is defined as the location which is most often fixated on within a word. A common finding is that observers preferentially fixate

slightly right or left of the word center, depending on the word length (Nuthmann, Engbert, & Kliegl, 2005), whereas the probability of fixating on the first and last letters of a word is lower. The IOVP effect represents the finding that the duration of the fixations near the edges of the words tends to be shorter.

In order to investigate the presence of those two phenomena when observers read drifting text, we performed a word-location-based analysis of our data. To this end, we collected all the fixations and smooth-pursuit episodes from the two experiments. In the case of the horizontally drifting text, the attribution of a smooth-pursuit episode to a word location was done by comparing the average horizontal position of gaze and text during the whole episode. In the case of the vertically drifting text, the smooth-pursuit episodes were attributed to a line if the average absolute distance between the gaze and the center of a given line was smaller than 42.3 arcmin. In general, we discarded from the analysis fixations and smooth-pursuit episodes landing on interword spaces and outside of the lines; we also discarded the fixations and pursuit episodes whose duration was either shorter than 30 ms or longer than 1000 ms. Furthermore, we only considered the fixations and pursuit episodes landing on words whose length was between 5 and 10 characters.[1] The number of saccades/pursuit episodes corresponding to the different criteria in the horizontally drifting text experiment is reported in Table 6.

The probability of the first fixation on a word landing in a particular relative position in the horizontally drifting experiment is plotted in Figure 11A. While the classical bell-shaped PVL curve was evident for the case when observers read the stationary

Condition	Total	On text	First fixations	Nonduration outliers	On selected words
Stationary	20,486	19,017	7,316	7,293	3,708
10.57°/s	22,162	19,918	12,253	12,227	8,290
14.09°/s	16,844	15,137	10,537	10,519	6,806

Table 6. Number of fixations and smooth-pursuit episodes in the horizontally drifting text experiment for the analysis of the preferred viewing location and the inverted optimal viewing position. Only the fixations and pursuit episodes landing within words of 5 to 10 characters were analyzed.

text, the targeting of the words appeared less precise when the text was drifting, and fixations landed more often on the right half of the word. In order to fit the data with a Gaussian model, we constrained the fits of the mean parameters (which we take as an indication of the PVL peak location) between 0 and 1. A one-way repeated-measure ANOVA with text speed (static, 10.57°/s, or 14.09°/s) as a factor evidenced that the mean parameter (i.e., the PVL peak) shifted depending on text motion, $F(2, 22) = 3.874$, $p < 0.036$, $\eta^2 = 0.26$), although further post hoc comparisons fail to demonstrate significance [static vs. 10.57°/s: $t(11) = 0.007$, $p = 1$; static vs. 14.09°/s: $t(11) = 2.512$, $p = 0.087$; 10.57°/s vs. 14.09°/s: $t(11) = 2.451$, $p = 0.096$]. The standard deviation of the Gaussian fits quantifies the precision of saccade targeting and the strength of the PVL. It was influenced by text motion, $F(2, 22) = 6.236$, $p < 0.007$, $\eta^2 = 0.36$. Further post hoc comparisons indicate that the standard deviation of the PVL was larger when the text was drifting at 10.57°/s, $t(11) = 2.962$, $p < 0.039$, and when the text was drifting at 14.09°/s, $t(11) = 4.923$, $p < 0.001$, as compared to when the text was stationary. The standard-deviation values did not differ between the trials where the text drifted at 10.57°/s and at 14.09°/s, $t(11) = 1.615$, $p < 0.403$. These results indicate that the PVL was more variable and shifted to the right for horizontally drifting text. This could be taken as evidence for less precise saccade targeting with horizontally drifting text. The shift to the right is consistent with the finding that saccade amplitudes were not different between static and horizontally drifting text. Since the text was drifting opposite to the saccade direction, equal saccade amplitudes have to result in viewing locations shifted to the right compared to static texts.

The average duration of fixations depending on the relative position of landing within the word is plotted in Figure 11B. The classical IOVP effect appeared in all conditions, and the largest costs in terms of fixation duration appeared to be shifted towards the initial part of the word in the case of the static text. The data were fitted with a three-parameter model (Nuthmann et al., 2005):

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

The model parameters describe the fixation-duration offset (A), width of the curve (B), and peak of the curve (C). Similarly to the case of the PVL, we constrained the fits of the peak parameter (C) between 0 and 1.

A one-way repeated-measure ANOVA with text speed (static, 10.57°/s, or 14.09°/s) as a factor showed a significant effect on the C parameter, $F(2, 22) = 3.645$, $p < 0.042$, $\eta^2 = 0.24$, suggesting that text motion induced a rightward shift of the IOVP, although further post hoc comparisons fail to demonstrate significance [static vs. 10.57°/s: $t(11) = 2.714$, $p = 0.060$; static vs. 14.09°/s: $t(11) = 1.532$, $p = 0.460$; 10.57°/s vs. 14.09°/s: $t(11) = 1.141$, $p = 0.834$]. The width of the IOVP curves (B parameter), however, was not influenced by text motion, $F(2, 22) = 0.506$, $p = 0.609$, $\eta^2 = 0.04$.

The number of fixations and smooth-pursuit episodes that we collected and which passed the selection criteria in the vertically drifting text experiment are represented in Table 7. Notice that fewer episodes per condition were collected as compared to the horizontally drifting text experiment. The relative probability of fixations landing in different parts of the word is represented in Figure 12A and B. The peak of the PVL function appeared slightly more centered in the word when the text was drifting upwards. The same Gaussian model as

Text speed	Text-motion direction	Total	On text	First fixations	Nonduration outliers	On selected words
3.52°/s	Upward	12,502	9,663	6,119	6,110	3,039
3.52°/s	Static	12,137	8,481	5,399	5,379	2,702
3.52°/s	Downward	12,703	8,567	5,352	5,343	2,540
7.05°/s	Upward	11,023	8,834	6,160	6,154	3,014
7.05°/s	Static	11,786	7,924	5,181	5,167	2,524
7.05°/s	Downward	11,509	7,636	5,264	5,260	2,627

Table 7. Number of fixations and smooth-pursuit episodes in the vertically drifting text experiment for the analysis of the preferred viewing location and the inverted optimal viewing position. Only the fixations and episodes landing within words of 5 to 10 characters were analyzed.
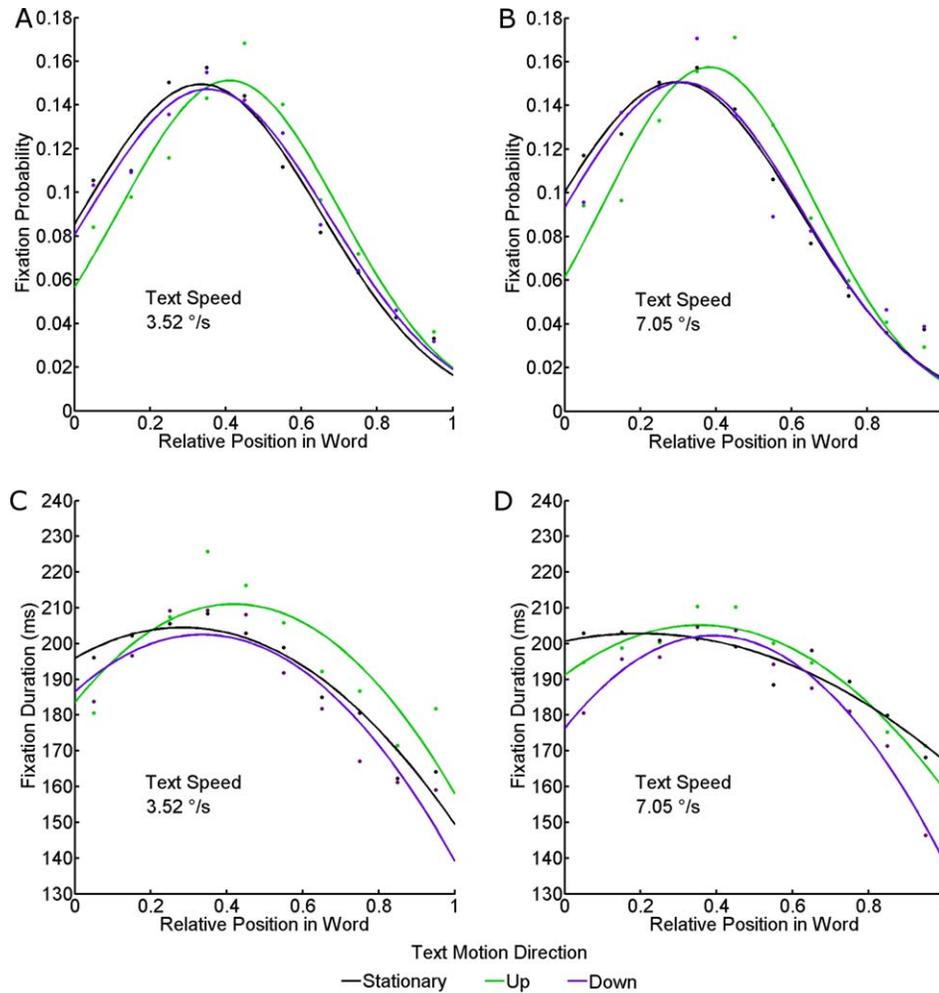
Figure 12. Preferred viewing location (A and B) and inverted optimal viewing position (C and D) in the vertically drifting text experiment. Data are aggregated for words whose length ranged between 5 and 10 characters. The solid lines are Gaussian model fits in (A) and (B) and three-parameter IOVP model fits in (C) and (D). The PVL in (A) and (B) appeared more centered in the upward-drifting text condition.

for the horizontally drifting text was used to fit the PVL function. The fitted values of the mean parameters were submitted to a repeated-measure two-way ANOVA with text-motion direction (upward, static, or downward) and text speed (3.52°/s vs. 7.05°/s) as factors. The analysis confirmed a main effect of text-motion direction on the PVL location [main effect of text-motion direction: $F(2, 22) = 4.187$, $p < 0.028$, $\eta^2 = 0.28$]. The effect did not depend on text speed [text speed × text-motion direction interaction: $F(2, 22) = 0.230$, $p = 0.796$, $\eta^2 = 0.02$], and the main effect of text speed was not significant, $F(1, 11) = 3.608$, $p = 0.084$, $\eta^2 = 0.25$). Post hoc comparisons fail to evidence significant differences between any pair of the three motion directions [static vs. upward: $t(11) = 2.316$, $p = 0.122$; static vs. downward: $t(11) = 0.130$, $p = 1$; upward vs. downward: $t(11) = 2.521$, $p = 0.085$]. The same analysis applied to the standard-deviation parameter failed to evidence any significant effect or interaction [main effect

of text speed: $F(1, 11) = 0.9$, $p = 0.363$, $\eta^2 = 0.08$; main effect of text-motion direction: $F(2, 22) = 2.786$, $p = 0.083$, $\eta^2 = 0.02$; text speed × text-motion direction interaction: $F(2, 22) = 1.782$, $p = 0.192$, $\eta^2 = 0.14$].

The duration of first fixations as a function of the relative landing point within a word in the vertically drifting text experiment is depicted in Figure 12C and D. Similar to what we observed in the case of the horizontally drifting text, the IOVP effect appeared more evident and more centered when the text was moving. The fitted values of the C parameter (IOVP peak) were submitted to a repeated-measure two-way ANOVA with text-motion direction (upward, static, or downward) and text speed (3.52°/s vs. 7.05°/s) as factors. The analysis failed to evidence any significant effect or interaction [main effect of text speed: $F(1, 11) = 0.297$, $p = 0.597$, $\eta^2 = 0.03$; main effect of text-motion direction: $F(2, 22) = 2.177$, $p = 0.137$, $\eta^2 = 0.17$; text speed × text-motion direction interaction: $F(2, 22) =$

1.368, $p = 0.275$, $\eta^2 = 0.11$]. By contrast, the same ANOVA performed on the B parameter (IOVP width) produced a significant effect of text-motion direction, $F(2, 22) = 6.210$, $p < 0.007$, $\eta^2 = 0.36$, whereas the main effect of text speed, $F(1, 11) = 2.403$, $p = 0.149$, $\eta^2 = 0.18$, and the two-way interaction, $F(2, 22) = 1.663$, $p = 0.212$, $\eta^2 = 0.13$, were not significant. Post hoc comparisons evidence that the IOVP function was less peaked when the text was stationary as compared to when the text drifted downward, $t(11) = 3.387$, $p < 0.018$, whereas the other tests were not significant [static vs. upward: $t(11) = 1.967$, $p = 0.224$; upward vs. downward: $t(11) = 1.498$, $p = 0.487$].

Discussion

This study investigated saccadic and smooth-pursuit eye movements and their interaction during the reading of drifting texts. As a comparison, we used self-paced reading of static texts and static texts for which the line length and presentation rate were adjusted to impose similar reading speeds as for the drifting texts. Text motion was either horizontal (leftward, i.e., opposite to the reading direction) or vertical (upward and downward). Our results show that well-known low-level oculomotor phenomena, such as postsaccadic pursuit enhancement, that have been observed with simple laboratory stimuli also apply to the more complex situation of reading drifting texts. Moreover, classical eye-movement patterns in normal reading, such as the correlation between saccade amplitude and subsequent fixation duration, the preferred viewing location, and the inverted optimal viewing position also transferred to the reading of drifting texts.

Smooth-pursuit eye movements

Consistent with previous studies on the reading of drifting texts (Buettner et al., 1985; Sun & Feng, 1999; Öquist & Lundin, 2007), we found that fixations during normal reading were replaced by smooth-pursuit eye movements. For horizontally drifting text, fixation/pursuit durations were increased by about 15–20 ms compared to the static condition (Figure 3). This increase in pursuit duration might indicate that more time was necessary to recognize words when the text was drifting horizontally. For vertically drifting text, fixation/pursuit durations were mainly affected by the line length and did not differ between the static and drifting conditions. Most importantly, fixation/pursuit durations for individual observers were highly correlated between the self-paced pretest and the experimental conditions for both horizontally and vertically

drifting text. This means that individual reading patterns were similar for static and drifting texts and that our experimental conditions did not destroy these individual patterns.

The gain of smooth pursuit varied overall between 0.9 and 1.1 (Figure 5). This means that the retinal speed of the text varied between 0.09°/s and 0.92°/s, depending on pursuit gain and drift speed. These values are well below the critical value of 2.5°/s, at which spatial acuity deteriorates rapidly (Westheimer & McKee, 1975). The increase of contrast sensitivity for high-spatial frequencies during smooth pursuit (Schütz, Braun, Kerzel, & Gegenfurtner, 2008; Schütz, Braun, & Gegenfurtner, 2009a) might also facilitate reading under these challenging conditions. Taken together with the similar level of reading comprehension, our static- and drifting-text conditions were comparable in reading difficulty. This is also consistent with a previous study that observed only small impairments of letter recognition during smooth pursuit (Schütz, Braun, & Gegenfurtner, 2009b).

Interestingly, pursuit gain was increased by 8.5% after the execution of a saccade. Such a postsaccadic pursuit enhancement has been observed previously during pursuit initiation in response to a single target (Lisberger, 1998). Our results suggest that this postsaccadic pursuit enhancement occurs also during steady-state pursuit and when a more complex stimulus is tracked. A report of enhanced motion sensitivity in area MT after the execution of a saccade (Ibbotson, Price, Crowder, Ono, & Mustari, 2007) suggests that saccades increase the gain of motion processing in general. Surprisingly, postsaccadic pursuit gain even exceeded unity in some conditions, meaning that the eyes were moving faster than the text itself. It might be that postsaccadic pursuit compensates small position errors after the execution of saccades.

For vertically drifting text, pursuit gain was lower for the faster motion. Since all text speeds were much lower than the upper limit of smooth pursuit—about 100°/s (Meyer, Lasker, & Robinson, 1985)—it is unlikely that the reduced gain for the faster motion is caused by a saturation of eye velocity. Alternatively, the differences in pursuit gain might be caused by the range of tested speeds (Kowler & McKee, 1987), such that pursuit gain was increased for the lower speeds and decreased for the faster speeds. However, the different speeds and directions were presented in separate blocks, so that potential range effects could have affected pursuit gain only across blocks.

Saccadic eye movements

For horizontal motion, saccade amplitudes were not different from those with static texts when measured in

degrees of visual angle (Figure 7). Since the text was moving opposite to the reading direction, this means that the saccade amplitudes were larger for drifting text when measured in characters. This finding is consistent with the rightward shift of the PVL for horizontally drifting text (see later discussion). For vertical motion, saccade amplitudes were mainly affected by line length, such that conditions with longer lines yielded, on average, larger saccade amplitudes. However, the vertical component of saccades was precisely scaled to the vertical drift of the text during the saccade (Figure 6). This allowed a precise targeting of the individual text lines, even when they were moving vertically. Like the fixation/pursuit durations, saccade amplitudes were highly correlated between the self-paced pretest and the experimental conditions for both horizontally and vertically drifting text. This is further evidence that the individual reading behavior was similar for static and drifting texts and that our experimental manipulation did not completely normalize the individual reading behavior.

We also investigated how reading of drifting texts affects the main sequence of saccades (Bahill et al., 1975), that is, the relationship between saccade amplitude and peak velocity. In the horizontally drifting text condition, smooth-pursuit eye movements were executed to the left, whereas saccadic eye movements were executed to the right. As expected from a combination of pursuit and saccades, we found reduced saccade peak velocities for the drifting-text conditions (Figure 10). This is in line with previous reports showing that pursuit alters the main sequence of saccades (de Brouwer et al., 2002). In the vertically drifting text condition, smooth pursuit and the main component of the saccades were oriented orthogonally. Consequently, we did not find any significant difference in peak velocity between static and drifting conditions. However, saccade peak velocity was increased for the static and drifting conditions with shorter line length. Taken together with the shorter fixation/pursuit durations in the same conditions, these differences probably reflect the increased time pressure due to the faster presentation rate.

Effects known from the reading of static texts

Some of the properties of normal reading of static texts also apply to the reading of drifting texts. We observed a positive correlation of fixation/pursuit duration and the previous saccade amplitude (Figure 8), as has been shown before for static texts (Pollatsek, Rayner, & Balota, 1986; Radach & Heller, 2000; Vitu et al., 2001; Kliegl, Nuthmann, & Engbert, 2006). The increase of fixation/pursuit duration with increasing incoming saccade amplitude can be taken as an estimate of the amount of parafoveal-preview benefit.

Hence our observers benefitted from parafoveal preview, even with drifting texts. A similar finding has been obtained by manipulating the size of the foveal window (Fine, Woods, & Peli, 2001). Since the slope of fixation/pursuit duration over incoming saccade amplitude was identical for drifting text and static text, there was presumably no difference in the amount of parafoveal-preview benefit. Further support for a similar parafoveal preview for static and drifting texts comes from the finding that the size of the crowding zone is similar for static and drifting characters (Bex, Dakin, & Simmers, 2003).

We also analyzed the fixation probability and fixation durations within single words. Like for the reading of static texts, we found a PVL (Rayner, 1979) at the center of words. For horizontal drifting text, the PVL was shifted to the right compared to static text (Figure 11). Since the text was drifting opposite to the saccade direction, this means that text motion was not completely compensated for by the saccades. This is consistent with the finding that saccade amplitudes were not reduced when the text was drifting horizontally. The overall longer smooth-pursuit episodes for horizontally drifting text might be caused by these nonoptimal landing positions within the words. When the text was drifting vertically, the PVL was remarkably similar to the case of the reading of static text (Figure 12). We also found evidence for an IOVP (Vitu et al., 2001; Nuthmann et al., 2005) during the reading of drifting texts. Like for the reading of static texts, smooth-pursuit durations were increased for pursuit episodes at the center of words compared to pursuit episodes at the edges of words. For horizontally drifting text, the IOVP was shifted to the right (Figure 11) compared to static texts, consistent with the shift in PVL. For vertically drifting text, the IOVP was very similar to that in the reading of static text (Figure 12).

Conclusions

We have shown that the reading of drifting texts is accomplished by an alternation of smooth and saccadic eye movements. These eye movements are not executed in isolation, but interact with each other. Pursuit gain is increased after the execution of a saccade, and the amplitude of the preceding saccade determines the duration of the following pursuit episode, just like in the reading of static texts. The peak velocity of saccades is reduced for horizontally drifting text, as expected by a simple summation of smooth pursuit and saccades. The preferred viewing location and the inverted optimal viewing position are shifted to the right for horizontally drifting text but are very similar for vertically drifting and static texts.

Acknowledgments

Footnote

[1]The current paradigm was devised with the aim of investigating steady-state reading of drifting text, and to this end we had to sacrifice part of the eye-tracking system's accuracy. This is due both to the fact that we had our observers read quite lengthy paragraphs without intervening drift corrections and, particularly in the case of the vertically drifting text, to the fact that observers fixated on the text preferentially in different parts of the screen (thus inflating the effect of imprecise calibration) depending on the condition. In order to limit the impact of low eye-tracking accuracy on the analyses at hand, we decided to limit our analysis to relatively long words, for which resolution is less critical. Moreover, since we tested a relatively large number of conditions, we decided not to further split our data based on word length before fitting the PVL and IOVP curves. Including words with length shorter than five characters introduced noise in the data but no qualitative difference.

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