Chapter 17

Using the Saccadic Inhibition Paradigm to Investigate Saccadic Control in Reading

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In two experiments, during reading, 33 ms. flickers occurred to the left or the right of the point of gaze at random intervals. We documented a decrease in saccadic frequency following the onset of this task-irrelevant flicker. This effect was referred to as saccadic inhibition. It was found that the saccadic inhibition effect differed depending on whether the flickers were congruent or incongruent with the direction of the next saccade. Specifically, a large flicker produced a stronger inhibition in the congruent than the incongruent condition, whereas the reverse was true for a small flicker. The implications of these findings for models of saccadic control in reading are discussed.

Introduction

Models of saccadic control in reading differ dramatically with respect to the hypothesized role of visuo-spatial attention in the programming and execution of eye movements (see Rayner, 1998 for a review). The attentional guidance model postulates tight coupling between attention and saccadic control in reading. An early version of this model, proposed by Morrison (1984; see also Just & Carpenter, 1980), argued that an attention shift in the direction of the next saccade occurs prior to its execution. Specifically, this model assumes that attention is initially centered on the foveated word (word N) during fixation. Following lexical encoding of the fixated word, attention covertly shifts in the direction of reading and a saccade aimed at fixating the newly attended word (word N+1) is programmed. If parafoveal lexical encoding of word N+1 is completed prior to the execution of the next saccade, attention further shifts to word N+2 and a new saccade aimed at fixating word N+2 is programmed. In such
instances either word $N+1$ is skipped (i.e., the $N$ to $N+1$ saccade is canceled) or, if the point of no return is exceeded, word $N+1$ is only briefly fixated on route to fixating word $N+2$ (see Rayner & Pollatsek, 1989 for a review and discussion). Morrison’s (1984) model was very influential and several modified versions aimed at extending it were proposed (e.g., Henderson, 1992; Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Pollatsek & Rayner, 1990; Rayner & Pollatsek, 1989; Reichle, Pollatsek, Fisher & Rayner, 1998). In addition, alternative models were formulated, which assumed that nonlexical, low-level information determines saccadic control in reading (e.g., Kowler & Anton, 1987; McConkie, Kerr, Reddix & Zola, 1988; McConkie, Kerr, Reddix, Zola & Jacobs, 1989; O’Regan, 1990, 1992). Such models argued that the influence of higher-level cognitive or attentional processes on saccadic control in reading is very limited. Currently, the issue of the relationship between attention and saccadic control in reading remains controversial (e.g., Brysbaert & Vitu, 1998; Deubel, O’Regan & Radach, 2000; Kliegl & Engbert, in press; McConkie & Yang, in press; Pollatsek, Reichle & Rayner, in press; Rayner, 1998; Reilly & Radach, in press; Vitu, O’Regan, Inhoff & Topolski, 1995; Vitu & O’Regan, 1995).

One clear prediction that can be derived from the attentional guidance model is the occurrence of perceptual enhancement in the direction of the next saccade, due to preallocation of attention to the target of the saccade. In order to empirically test this prediction, Fischer (1999) introduced the dynamic orienting paradigm. During reading, a probe (an asterisk appearing just above a line of text) was presented with a delay of either 25 ms. (early probe conditions) or 170 ms. (late probe conditions) following the onset of a randomly selected fixation (see Panel A of Figure 17.1). Participants were required to indicate probe detection with a speeded manual response. Reading comprehension and probe detection were designated as primary and secondary tasks respectively in this dual task paradigm. The spatial location of the probe was either 5 or 10 characters to the left (incongruent conditions) or the right (congruent conditions) of the participants’ gaze position, or directly above the fixated character. Based on the attentional guidance model, Fischer (1999) predicted that if the probe is presented late in the fixation following the preallocation of attention to the next saccadic target (words $N+1$ or $N+2$), faster probe detection reaction times (RTs) should be obtained when the probe was displayed in a location congruent with the direction of reading than when it was presented in the opposite direction. If, however, the probe is presented early in the fixation, before attention is preallocated, no such difference should be seen. This pattern was successfully demonstrated in a visual search condition in which participants searched for target letters embedded in reading-like displays of horizontal letter strings. In contrast, the predicted pattern of results was not obtained in either a reading condition (i.e., where participants read for comprehension) or a “mindless reading” condition (i.e., where all letters in the text were replaced by the letter “z” and participants pretended to read these z-strings; see Rayner & Fischer, 1996; Vitu et al., 1995). In addition, across all three primary tasks (visual search, reading, and mindless reading) and for both the early and late probe conditions it was demonstrated that probes interfered with eye movements producing longer fixations and shorter saccades. Furthermore, this interference was attenuated when the probe was presented near the location of the next saccadic target (i.e., in the congruent conditions) as compared to
when the probe was presented in the opposite hemifield (i.e., in the incongruent conditions). Importantly, if this congruency effect (i.e., the smaller interference in congruent than incongruent conditions) was due to the preallocation of attention to the next saccadic target it should have been demonstrated in late probes but not in early probe conditions. However, the size of the congruency effect was fairly comparable across the late and early probe conditions. Thus, probe detection performance and oculomotor behaviour documented by Fischer (1999) did not provide support for the predictions of the attentional guidance model.

In contrast to the findings reported by Fischer (1999), Reingold and Stampe (in press) documented perceptual enhancement in the direction of the next saccade in reading and the magnitude of this enhancement was shown to be influenced by higher level cognitive or attentional task demands. This study employed the saccadic inhibition paradigm (Reingold & Stampe, 1997, 2000, 2002, in press; Stampe & Reingold, in press) (see text for details).

Figure 17.1: Panel A illustrates the timing of probe presentation in the dynamic orienting paradigm (Fischer, 1999) and Panel B illustrates the display change timing in the saccadic inhibition paradigm (Reingold & Stampe, 1997, 2000, 2002, in press; Stampe & Reingold, in press) (see text for details).
the proportion of saccades remained constant. Approximately 60 to 70 ms following
the onset of the display change, the proportion of saccades decreased below this
initial level forming a dip that reflects saccadic inhibition. Following the dip, an
increase above the initial level of saccadic frequency occurred, forming a peak, which
likely reflects the recovery from inhibition. Finally, following the peak, the propor-
tion of saccades returned to initial levels. Reingold and Stampe (in press) devised and vali-
dated a variety of quantitative measures of the strength and latency of the saccadic
inhibition effect. Two of the measures that are the most relevant for the present inves-
tigation are illustrated in Figure 17.2. The magnitude of saccadic inhibition was defined
as the proportion of saccades inhibited when inhibition was at its maximum (i.e., at
the centre of the dip) and the duration measure was defined as the temporal interval
during which inhibition was greater than or equal to 50% of its magnitude.

Reingold and Stampe (in press) documented that the saccadic inhibition effect
varied as a function of the saliency of the visual event, with more salient display
changes producing stronger and more sustained inhibition. Most importantly, saccadic
inhibition was also shown to be sensitive to higher-level cognitive or attentional
factors. Specifically, in a reading condition, the magnitude of saccadic inhibition was
22.8% stronger and its duration was 22.7% longer when the display change (a flicker
displayed within the boundaries of a gaze contingent, 10° square window; see Panel
A of Figure 17.3) location was congruent with the direction of the saccade, relative to
when the flicker was incongruent with the direction of the saccade. In contrast, the corresponding congruency effects in a mindless reading condition were only 6.5% and 11.7% for the magnitude and duration measures respectively.

Figure 17.3: Results of Experiment 1. Panel A shows the black congruent flicker (top) and the black incongruent flicker (bottom); (the cross represents point of gaze in each image). Panel B shows the luma congruent flicker (top) and the luma incongruent flicker (bottom); (the cross represents point of gaze in each image). Panel C plots the histogram of normalized saccadic frequency following the flicker onset in the black congruent, black incongruent, luma congruent, and luma incongruent conditions (see text for details).
The goal of the present paper was to replicate and extend the findings reported by Reingold and Stampe (in press). In addition, the present investigation attempted to empirically identify some of the factors that may account for the dissimilar patterns of results obtained by Fischer (1999) and Reingold and Stampe (in press). As follows, there are important differences between these studies that may hold some explanatory value. In Fischer’s (1999) study, participants were required to respond to the probe (i.e., a dual task condition), whereas in the experiments conducted by Reingold and Stampe (in press), the flicker was irrelevant and participants were instructed to ignore it. In addition, the size of the probe was very small (an asterisk appearing above a letter), whereas the flicker covered a 10° square. Furthermore, in Fischer’s (1999) study, the appearance of the probe was time-locked to the beginning of fixation (See Panel A Figure 17.1), whereas in the experiments conducted by Reingold and Stampe (in press), the flicker occurred at a random delay from the beginning of fixation (See Panel B Figure 17.1). In the present experiments, we demonstrate that the difference in size between the flickers used by Reingold and Stampe (in press) and the probes employed by Fischer (1999) account at least in part for the differences in the pattern of findings obtained across studies.

Experiment 1

This experiment was designed to replicate the basic congruency effect reported by Reingold and Stampe (in press). The display change used was a flicker that was displayed within the boundaries of a gaze contingent, 10° square window that was displaced such that its nearest edge was 1° to the left or right of the point of gaze. For left to right saccades in English (i.e., forward saccades), the flicker to the left is incongruent and the flicker to the right is congruent with the direction of the saccade. According to the prediction of the attentional guidance model, a congruent flicker will be perceptually enhanced, whereas an incongruent flicker will be attenuated, leading to stronger inhibition in the congruent condition relative to the incongruent condition. This is the pattern demonstrated by Reingold and Stampe (in press). In the present experiment another variable was added to the design. Specifically, participants were reading black text presented on a gray background and the flicker was created by changing the background into black (as was the case in the experiments conducted by Reingold & Stampe, in press; see Panel A of Figure 17.3) or by changing the background into white (see Panel B of Figure 17.3). These black versus luma flicker conditions differed in that the text disappeared in the former, but not in the latter, condition. By comparing the congruency effect across these conditions it would be possible to determine the influence of the disappearance of the text, if any, on the size of this effect.

Method

Participants A group of 10 participants were tested. All participants had normal or corrected to normal vision, and were paid $10.00 per hour for their participation.
**Apparatus** The SR Research Ltd. EyeLink eye tracking system used in this research has a sampling rate of 250 Hz (4 ms temporal resolution). The EyeLink system uses an Ethernet link between the eye tracker and display computers, which supplies real-time gaze position data. The on-line saccade detector of the eye tracker was set to detect saccades with an amplitude of 0.5° or greater, using an acceleration threshold of 9500°/sec² and a velocity threshold of 30°/sec. Participants viewed a 17" (43 cm) ViewSonic 17PS monitor from a distance of 60 cm, which subtended a visual angle of 30° horizontally and 22.5° vertically. The display was generated using an S3 VGA card, and the frame rate was 120 Hz.

During the flicker, a gaze contingent window was used to limit the transient image to a 10° square area that was displaced such that its nearest edge was 1° to the left (incongruent) or right (congruent) of the point of gaze (see Panels A and B of Figure 17.3). As participants moved their eyes, their gaze position on the display was computed and used to set the region in which the transient image would be displayed during the next flicker. The average delay between an eye movement and the update of the gaze-contingent window was 14 ms.

**Materials and randomization** Participants read a short story for comprehension. The text was presented in black on a gray background. Anti-aliased, proportional spaced text was used with an average of three characters per degree of visual angle and an average of 10 lines of text per page. Each trial displayed one page of text in the story, with pages presented in the same order to all participants. Participants read a total of 100 pages of text, with 50 pages randomly assigned to each of the two flicker conditions (black, luma). The pairing of pages to conditions was determined randomly for each participant, constrained to allow no more than three contiguous trials of the same condition. For each of these flicker conditions the direction of the flicker (i.e., to the left or the right of current gaze position) varied randomly across consecutive display changes. Display changes lasted for 33 ms and occurred at inter-flicker intervals that varied randomly between 300 to 400 ms.

**Procedure** A 9-point calibration was performed at the start of the experiment followed by a 9-point calibration accuracy test. Calibration was repeated if the error at any point was more than 1°, or if the average error for all points was greater than 0.5°. Participants were instructed to read the text for comprehension. They were told that they would be asked questions about the content of the story when they finished reading. On average participants answered over 95% of these questions accurately, indicating that they complied with the instructions and were not simply scanning the text. After reading each page, participants pressed a button to end the trial and proceed to the next page of the story.

**Data analysis** The timing of the display changes was recorded along with eye movement data for later analysis. Eye tracker data files were processed to produce histograms of saccade frequency as a function of latency from the display change. Only forward saccades were included in the analysis. A separate histogram was compiled for each participant and condition, and analyzed to produce the magnitude
duration measures of the evoked saccadic inhibition (see Figure 17.2). Forward saccades following a flicker to the left were classified as part of the incongruent conditions and forward saccades following a flicker to the right were classified as part of the congruent conditions.

Results and Discussion

Panel C of Figure 17.3 presents the normalized saccadic frequency histograms for all four experimental conditions, and the derived saccadic inhibition measures (magnitude, duration) are shown in Table 17.1. For each of these dependent variables, a 2 × 2 within participants ANOVA, which crossed flicker congruency (congruent versus incongruent) by flicker type (black versus luma), was performed. Most importantly, as can be seen in Figure 17.3, when the direction of the saccade is congruent with the flicker, a stronger and more sustained inhibition results, and this congruency effect is quite similar across the black and luma flicker conditions. Consistent with this observation, the main effect of congruency was significant (magnitude: $F(1, 9) = 95.15, p < 0.001$; duration: $F(1, 9) = 11.86, p < 0.01$) and the interaction between congruency and flicker type was not significant for both the magnitude and duration measures (both $F_s < 1$). In addition, the black flicker produced stronger and more sustained inhibition than the luma flicker (magnitude: $F(1, 9) = 11.34, p < 0.01$; duration: $F(1, 9) = 16.93, p < 0.01$), probably due to the greater saliency of the former relative to the latter display change (see Reingold & Stampe, in press; Stampe & Reingold, in press). Thus, the present experiment replicated the congruency effect reported Reingold and Stampe, (in press) and demonstrated that the disappearance of the text has no influence on the size of this effect.

Table 17.1: Means and standard errors of the magnitude and the duration of saccadic inhibition across conditions in Experiments 1 and 2.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Condition</th>
<th>Saccadic Inhibition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Magnitude</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Proportion</td>
</tr>
<tr>
<td>Experiment 1</td>
<td>Black congruent</td>
<td>0.856 (0.024)</td>
</tr>
<tr>
<td></td>
<td>Black incongruent</td>
<td>0.719 (0.040)</td>
</tr>
<tr>
<td></td>
<td>Luma congruent</td>
<td>0.796 (0.031)</td>
</tr>
<tr>
<td></td>
<td>Luma incongruent</td>
<td>0.689 (0.030)</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>Small congruent</td>
<td>0.497 (0.054)</td>
</tr>
<tr>
<td></td>
<td>Small incongruent</td>
<td>0.632 (0.037)</td>
</tr>
<tr>
<td></td>
<td>Large congruent</td>
<td>0.886 (0.017)</td>
</tr>
<tr>
<td></td>
<td>Large incongruent</td>
<td>0.759 (0.025)</td>
</tr>
</tbody>
</table>
Experiment 2

As mentioned earlier, Fischer (1999) reported that the probes used in his paradigm interfered with eye movements producing longer fixations and shorter saccades and that this interference was greater when the probe was incongruent with the direction of the next saccade as compared to when the probe was congruent with the direction of the next saccade. In contrast, the congruency effect documented by Reingold and Stampe (in press), and replicated in Experiment 1, reflects stronger interference in the congruent than the incongruent condition. The present experiment was designed to investigate if the difference between the large flicker and the small probe may account for the dissimilar patterns of results obtained by Fischer (1999) and Reingold and Stampe (in press). In this experiment two flicker conditions were used: a 10° square flicker identical to the black flicker condition used in Experiment 1 and employed by Reingold and Stampe (in press), and a 1° square flicker presented centered 4° to the left or the right of the current gaze position (see Panels A and B of Figure 17.4).

Method

General A group of 10 participants who had not taken part in Experiment 1 was tested. All participants had normal or corrected to normal vision, and were paid $10.00 per hour for their participation.

Participants read a total of 100 pages of text, with 50 pages randomly assigned to each of the two flicker conditions (10° square, 1° square). The pairing of pages to conditions was determined randomly for each participant, constrained to allow no more than three contiguous trials of the same condition. For each of these flicker conditions the direction of the flicker (i.e., to the left or the right of current gaze position) varied randomly across consecutive display changes. All other aspects of the design, procedure, and data analysis were identical to Experiment 1.

Results and Discussion

Panel C of Figure 17.4 presents the normalized saccadic frequency histograms for all four experimental conditions, and the derived saccadic inhibition measures (magnitude, duration) are shown in Table 17.1. For each of these dependent variables, a 2 × 2 within participants ANOVA, which crossed flicker congruency (congruent versus incongruent) by flicker size (large: 10° square, small: 1° square), was performed. Most importantly, the interaction between congruency and flicker size was significant for both the magnitude ($F(1,9) = 36.29, p < 0.001$) and the duration ($F(1,9) = 6.73, p < 0.05$) measures. As can be seen in Figure 17.4, a dramatic reversal occurred in the direction of the congruency effect as a function of flicker size. Specifically, the large flicker condition replicated the results of Experiment 1 producing a stronger and more sustained inhibition in the congruent than in the incongruent condition (magnitude: $t(9) = 6.37, p < 0.001$; duration: $t(9) = 4.21, p < 0.01$). In contrast, for the small flicker
Figure 17.4: Results of Experiment 2. Panel A shows the small congruent flicker (top) and the small incongruent flicker (bottom); (the cross represents point of gaze in each image). Panel B shows the large congruent flicker (top) and the large incongruent flicker (bottom); (the cross represents point of gaze in each image). Panel C plots the histogram of normalized saccadic frequency following the flicker onset in the small congruent, small incongruent, large congruent, and large incongruent conditions (see text for details).
the incongruent condition produced a stronger inhibition than the congruent condition, and the congruency effect for duration was not significant (magnitude: $t(9) = 2.68$, $p < 0.05$; duration: $t < 1$). Thus, the results obtained with the large flicker replicate the pattern reported by Reingold and Stampe (in press), whereas the results obtained with the small flicker are consistent with the findings demonstrated by Fischer (1999).

**General Discussion**

The present findings replicated the congruency effect reported by Reingold and Stampe (in press). This effect is consistent with the prediction of the attentional guidance model of saccadic control in reading, which assumes that prior to the execution of saccades, attention is covertly preallocated to the saccadic target (e.g., Henderson, 1992; Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Morrison, 1984; Pollatsek & Rayner, 1990; Rayner & Pollatsek, 1989; Reichle *et al.*, 1998). Furthermore, these results are consistent with a growing body of research that suggests that whereas attention can be shifted covertly in the absence of eye movements, eye movements are preceded by an attentional shift to the saccadic target (e.g., Deubel & Schneider, 1996; Henderson, 1993; Hoffman, 1998; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher & Blaser, 1995; Rafal, Calabresi, Brennan & Sciolto, 1989; Rayner, McConkie & Ehrlich, 1978; Remington, 1980; Schneider & Deubel, 1995; Shepherd, Findlay & Hockey, 1986, but see Stelmach, Campsall & Herdman, 1997 for evidence against this preallocation hypothesis). This view concerning the link between the oculomotor and attentional systems is also supported by neurophysiological data (e.g., Goldberg & Wurtz, 1972; Kustov & Robinson, 1996; Mohler & Wurtz, 1976; Wurtz & Mohler, 1976) and work with neuropsychological populations such as neglect patients (e.g., Johnston & Diller, 1986; Walker & Young, 1996).

The present experiments extended the prior findings reported by Reingold and Stampe (in press) in two important ways. First, Experiment 1 clearly demonstrated that the disappearance of the text had no influence on the size of the congruency effect. Second, the results of Experiment 2 indicated that a crucial variable that mediated the direction of the congruency effect is the size of the sudden-onset (i.e., display change). Specifically, a large flicker produced a stronger inhibition in the congruent condition than in the incongruent condition, whereas the reverse was true for a small flicker. Further studies are required in order to investigate whether, as suggested here, the influence of flicker size on the congruency effect may account for the dissimilar patterns of results obtained by Fischer (1999) and Reingold and Stampe (in press). In addition, although empirically the effect of flicker size on the congruency effect has been convincingly demonstrated, currently, we can only speculate about the theoretical explanation for this finding. Reingold and Stampe (in press) interpreted the stronger inhibition in the congruent than the incongruent condition as resulting from a perceptual enhancement of the large flicker due to attentional preallocation in the direction of the next saccade. Fischer (1999) provided two potential explanations for the stronger interference in the incongruent than the congruent condition produced by the presentation of the small probe. The first explanation was based on the idea that
the sudden-onset probe redirects attention away from the intended saccadic target and 
that the cost of this attentional shift is greater in the incongruent condition due to the 
greater mismatch between the locations of the probe and the saccadic target. However, 
Fischer (1999) acknowledged that rather than attention, the effect of the probe on eye 
movements might be mediated by a low-level oculomotor effect known as the remote 
distractor effect. This effect signifies the slowing of saccadic reaction time (SRT), 
which occurs when a saccadic target and a distractor stimulus are presented simulta-
neously at different locations in the visual field. Importantly, SRTs are slower when 
the distractor is presented in the opposite hemifield than the target (this is the case 
in the incongruent probe conditions) than when the distractor is presented near the 
saccadic target (this is the case in the congruent probe conditions). Thus, an important 
goal for future research would be to attempt and disentangle these alternative expla-
nations. Finally, the present study illustrates the potential contributions of the saccadic 
inhibition paradigm to the study of higher-level cognitive or attentional factors that 
underlie reading.

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