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Inhibition of saccade return in reading

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Abstract

We examined the characteristics of readers' eye movements as they read sentences or short passages of text and compared the durations of eye fixations preceding two types of saccades: (a) saccades to words that were fixated on the prior fixation (return saccades) and (b) saccades in which the eyes moved about the same distance but did not land on a word fixated on the prior fixation (non-return saccades). Consistent with research from much simpler attention or oculomotor tasks, we found what could be considered an *inhibition of return* effect: fixations preceding return saccades were longer than those preceding non-return saccades.

Keywords: Saccades; Reading; Inhibition of return

1. Introduction

Posner and Cohen (1984) first observed that when attention is moved from one location to another in a visual array, processing of stimuli at a previously attended location is somewhat inhibited in comparison to a location that has not recently been attended. This inhibition effect, termed *inhibition of return* (Posner, Rafal, Choate, & Vaughan, 1985), often involves an increase in response latency to material in a previously attended region and presumably reflects the difficulty of returning attention to a previously attended location (for a review, see Klein, 2000).

While many inhibition of return studies have utilized reaction time measures, some have investigated the phenomenon by measuring eye movements in a visual array. For example, Abrams and Dobkin (1994) found that subjects were slower to initiate an eye movement to a previously attended location than to a previously unattended location (see also Maylor, 1985; Rafal, Egly, & Rhodes, 1994; Ro, Pratt, & Rafal, 2000; Vaughan, 1984). With respect to eye movements, Klein and MacInnes (1999) suggested that inhibition of return acts to facilitate visual search when multiple saccades are involved because it reduces the likelihood that the eyes will return to items that have been previously inspected.

Recently, Hooge and Frens (2000) extended this research area by examining the duration of fixations preceding saccades that took the eyes back to a previously fixated target. In their experiment, subjects had to fixate two to four targets in a fixed order as fast as they could. Some saccades were to a new (previously unfixated) target whereas other saccades took the eyes back to a target that had just been fixated. Hooge and Frens found that latencies for eye fixations preceding *return saccades* (saccades returning to the position that had just been fixated) were 40% longer than latencies of fixations preceding saccades to previously unfixated positions. They called the effect *inhibition of saccade return* and noted the similarity between their results and the more general inhibition of return effect (while noting that inhibition of saccade return seemed to be reset after each saccade whereas inhibition of return persists for up to two seconds). Of course, the standard inhibition of return phenomenon originally dealt with covert attention shifts, while inhibition of saccade return relates to saccadic eye movements. Nevertheless, Hooge and Frens suggested that the two phenomenon may have the same underlying neural mechanisms.

The question we address is: Does the inhibition of saccade return effect generalize to the more complex task of reading (where eye movements have been a particularly effective way to study moment-to-moment

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processing)? Are fixation durations increased before readers move their eyes to a word that they previously fixated? We thought that it would be quite remarkable if the effect generalized to reading because it is well-known that eye fixations in reading are quite sensitive to linguistic variables like word frequency and word predictability, which may dominate low-level effects like inhibition of return (see Liversedge & Findlay, 2000; Rayner, 1998; Starr & Rayner, 2001 for reviews).

Of course, it is impossible to control where readers fixate as they read and the extent to which they do or do not move their eyes back to a word that they have immediately just fixated. Therefore, the analyses we report are based on culling instances of return saccades from a large corpus of eye movement data from readers reading text or sentences under instructions to comprehend the reading material.

2. Method

2.1. Subjects

The eye movements of three groups of University of Massachusetts students were examined. The first group consisted of 20 students who read 48 short passages of text (typically consisting of around 50 words). The second and third groups each consisted of 24 students who read 144 sentences (consisting of 8–10 words). The sentences that the third group read contained either high or low frequency target words. All of the subjects had normal uncorrected vision.

2.2. Apparatus, materials, and procedure

Eye movements were recorded via a Fourward Technologies Dual Purkinje Eyetracker. The subject was seated 61 cm from a video monitor on which the sentence or text was displayed. At this viewing distance, 3.8 characters equaled one degree of visual angle. Although viewing was binocular, eye movements were recorded from only the right eye. The eyetracker has a spatial resolution of less than 10 min; eye position was sampled every millisecond and stored in the computer for later analysis.

The passages or sentences were presented on the video monitor and the subjects were asked to read them as they would normally read text. When they finished reading a passage or a sentence, they pushed a button that resulted in the erasure of that particular stimulus. On about 25% of the trials, the stimulus was followed by a short two choice comprehension question. Subjects responded to the comprehension question by pushing one of two buttons. After they pushed the button, a new passage or sentence appeared following a brief calibration check. If a particular passage or sentence was not followed by a comprehension question, the calibration check and the next passage or sentence appeared following the button press that erased the prior stimulus. The passages and sentences were designed for fairly easy reading and contained no syntactic or conceptual difficulties. This is important because we did not want stimulus materials that were difficult to comprehend and would therefore engender many regressive eye movements that reflected comprehension problems.

3. Results

For the first group of 20 readers, we compared fixations preceding regressive saccades (where the eyes returned to a previously fixated word) with fixations preceding regressive saccades (of roughly the same spatial distance) to a word that had been previously skipped. Regressions, which typically represent about 10–15% of the fixations in reading (Rayner, 1998), are assumed to occur for two reasons (Rayner, 1998): (a) the eyes sometimes overshoot their intended target and a short regressive saccade is initiated (these *corrective* saccades are typically quite short, covering only a letter or two, and are often intraword saccades), and (b) some aspect of the text was not understood (these so-called *comprehension* regressions are interword saccades to words on the same line as well as to words on a preceding line). To eliminate corrective saccades as well as saccades reflecting a major breakdown of comprehension, we limited our analyses to instances where the regression was at least 3 letter spaces (and, hence, unlikely to be due to an overshoot) but was no more than 15 letter spaces (and, hence, not as likely to be due to major comprehension breakdowns). To qualify as a return saccade, the eyes had to move from the current fixation back to the word that had just been fixated. We eliminated cases in which readers engaged in a series of two or more regressive eye movements, as well as regressions to the beginning or from the end of a passage/sentence.

In the cases just discussed, a saccade returns to a previously fixated word via a regression. We refer to these as regressive return saccades (RRS). In addition, we analyzed forward return saccades (FRS), in which a saccade takes the eyes forward in the text to a region from which they had originally regressed (which we term FRS). Fixations preceding these two types of return saccades were compared to fixations preceding regressive and forward saccades which did not return to the word fixated on the immediately preceding fixation (*regressive* and *forward non-return saccades*, RNS and FNS, respectively [1]). Table 1 presents the mean fixation

[1] A forward saccade was counted as a FRS or FNS only when it immediately followed a regression.

durations preceding the different types of saccades [2], and Fig. 1 shows the frequency distributions of fixation durations. Fixations preceding RRS were 36 ms longer than non-return regressive saccades, $t(19) = 4.65$, $p < 0.001$; those preceding FRS were 44 ms longer than non-return forward saccades, $t(19) = 4.31$, $p < 0.001$. The fact that FRS showed the same effect as RRS suggests that the effect is not simply due to readers not fully processing the word to which they regressed.

We examined whether there were any differences if the saccade went back to the exact same location (so that the eyes landed on exactly the same letter on the return saccade as they were on previously) or to a slightly different location. Of course, there were far fewer cases in which the eyes went to exactly the same letter position than cases in which they went to a different location. Nevertheless, for both regressive return saccades and FRS, the mean values did not differ by more than 5 ms between instances where the eyes returned to exactly the same letter as when they returned to a different letter. If the return saccade effect we have observed is truly an inhibition of return effect, its lack of dependence on individual letter location suggests that the inhibited region is defined in terms of a word, not in terms of an individual letter.

We also examined the average length of saccades to either the previously fixated or the skipped word. For regressive saccades, return saccade lengths averaged 6.9 letter spaces compared to 5.4 letter spaces for non-returns, $t(19) = 4.55$, $p < 0.001$. For forward saccades, return saccade length averaged 8.2 letter spaces compared to 9.7 letter spaces for non-returns, $t(19) = 4.29$, $p < 0.001$. The latter difference suggests that the longer fixations before return regressions were not simply due to longer saccades being programmed, but rather also presumably reflect the greater difficulty of return saccades. [3]

Table 1 also shows the data for the other two groups of readers (who read single sentences [4]). Here, it can be seen that the basic pattern of results reported above was replicated in these groups. For Group 2, fixations preceding RRS were 28 ms longer than non-return saccades, $t(23) = 2.31$, $p < 0.05$; those preceding forward return saccades were 48 ms longer than non-returns, $t(23) = 4.83$, $p < 0.001$. For this group, RRS lengths averaged 6.8 letter spaces compared to 5.2 letter spaces for non-returns, $t(23) = 3.65$, $p < 0.001$; FRS lengths averaged 8.6 letter spaces compared to 11.0 letter spaces for non-returns, $t(23) = 6.81$, $p < 0.001$. For Group 3, fixations preceding RRS were 20 ms longer than non-returns, $t(23) = 1.93$, $p = 0.06$; those preceding FRS were 45 ms longer than non-returns, $t(23) = 2.79$, $p < 0.01$. For this group, RRS lengths averaged 6.6 letter spaces compared to 5.6 letter spaces for non-returns, $t(23) = 2.28$, $p < 0.05$; FRS lengths averaged 8.4 letter spaces compared to 10.2 letter spaces for non-returns, $t(23) = 3.48$, $p < 0.001$.

In an attempt to determine if there was any indication that some type of global comprehension problem was responsible for the data, we also examined (1) the duration of the fixation prior to the fixation on which a return saccade was launched and (2) the length of the preceding saccade, and (3) the duration of the landing fixation. If the fixation on which readers launched a RRS (or non-return regressive saccade) is considered fixation n, the prior fixation can be considered as fixation $n - 1$. Likewise, the saccade preceding saccade n (the actual return or non-return saccade) can be thought of as saccade $n - 1$.

Examination of the $n - 1$ fixations revealed that for both Group 2 and Group 3, [5] fixation $n - 1$ was slightly inflated when fixation n preceded a regressive non-return saccade than when it preceded a RRS; across the two groups, the mean fixation duration was 272 ms for the fixation preceding a non-return and 263 ms preceding a return. If this slight elevation of fixation duration were significant, we would argue that it reflects the fact that fixations preceding word skipping are often somewhat inflated (see Pollatsek, Rayner, & Balota, 1986) and the non-return condition typically involved skipping a word. Nevertheless, it was the case that fixation $n - 1$ preceding a return saccade was not longer than the same fixation preceding a non-return saccade which would be

[2] These data are based on 1256 saccades for Group 1, 619 saccades for Group 2, and 630 saccades for Group 3. Of these, 58% were regressions and 42% were forward saccades, and 47% were return saccades and 53% were non-return saccades. Across all of the eye movement data examined, return saccades accounted for roughly 2–3% of all saccades.

[3] It is the case that the fixation duration data showed the same pattern for regressive and forward saccades, while the pattern differed for saccade length. In the case of regressions, saccade lengths were longer for return saccades as the eyes went a greater distance to get back to a previously fixated word than a skipped word. However, for forward saccades, saccade length was longer for non-return saccades than return saccades. This reflects the fact that when readers moved their eyes forward in the text following a regression, in the non-return case they typically moved their eyes beyond the word from which they initially regressed.

[4] The subjects in Group 2 came from a larger group of 64 subjects and those in Group 3 came from a larger group of 54 subjects. For Group 2, only those who contributed at least two data points to each cell mean were included in the analyses and for Group 3 only those who contributed at least one data point to each cell mean were included.

[5] For reasons unrelated to the analyses, it was not possible to analyze the data for the Group 1 readers.

Table 1
Mean fixation durations and saccade lengths

	Fixation duration[a]				Saccade length[b]			
	RRS	RNS	FRS	FNS	RRS	RNS	FRS	FNS
Group 1 ($N = 20$)	241	205	245	201	6.9	5.4	8.2	9.7
Group 2 ($N = 24$)	260	232	270	222	6.8	5.2	8.6	11.0
Group 3 ($N = 24$)	253	233	288	243	6.6	5.6	8.4	10.2
Mean	251	223	268	222	6.8	5.4	8.4	10.3

RRS = Regressive return saccade; RNS = Regressive non-return saccade; FRS = Forward return saccade; FNS = Forward non-return saccade.
[a] In milliseconds.
[b] In character spaces.

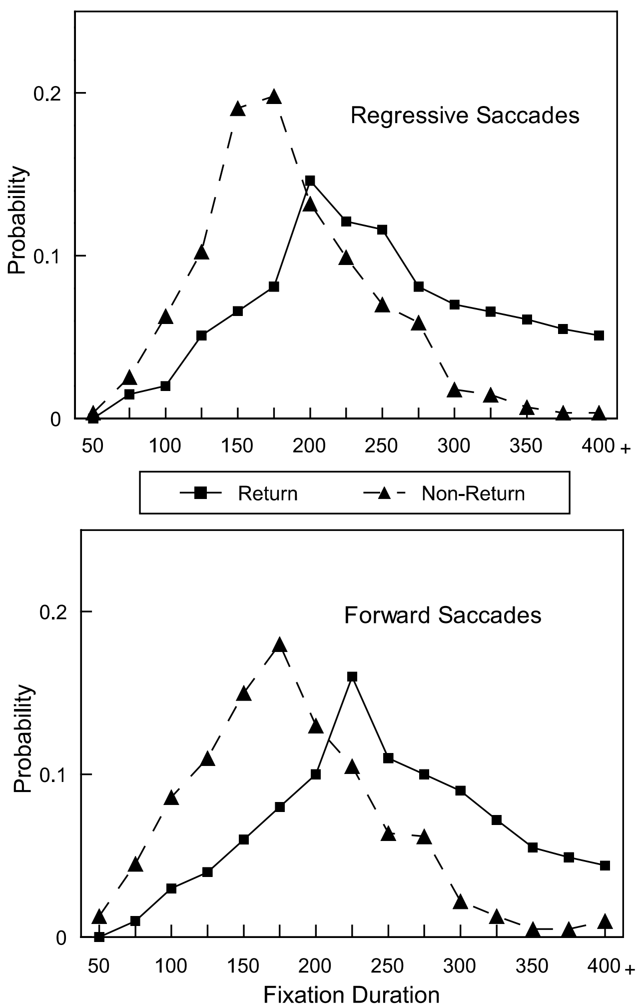

Fig. 1. Frequency distributions of fixation durations (or saccade latencies) for regressive saccades (upper panel) and forward saccades (lower panel) for return and non-return saccades for 20 readers reading short passages.

expected if some type of comprehension problem were responsible for the effect.

Examination of the length of the $n-1$ saccade indicated that it was longer when the next saccade was a regressive non-return saccade (12.4 letter spaces in Group 2 and 12.2 letter spaces in Group 3) than when it was a RRS (7.3 letter spaces in Group 2 and 7.3 letter spaces in Group 3), $t(23) = 4.74$, and $t(23) = 4.09$, $p < 0.001$. This difference basically reflects that the $n-1$ saccade preceding a regressive non-return saccade often involved skipping a word. Together, the data for fixation $n-1$ and saccade $n-1$ offer no indication that comprehension problems can account for the return effect we observed.

Finally, in addition to providing an independent replication of the basic return saccade effect, we were interested in Group 3 because, as noted above, these subjects read sentences which contained target words that were either high or low frequency (the high frequency words all had frequency counts larger than 152 per million and the low frequency words all had frequency counts less than 8 per million according to the Francis & Kuĉera, 1982). Thus, we examined the duration of fixations preceding a return or non-return saccade when the currently fixated word was either a high or low frequency word.

For this frequency-based analysis there were limited data to include in calculating the means. All analyses discussed to this point were based on all saccades from potentially all of the words in the text/sentences (eliminating regressions from the beginning and end words, as stated earlier). But, for the present analysis, we were restricted to saccades from the high or low frequency target words in a sentence. Furthermore, we were not able to do formal statistical tests since there were so little data per subject (or item for that matter). What we did was to calculate means using all of the data that were available. The resulting data reported next should therefore perhaps be considered as only suggestive. Nevertheless, these data suggest that frequency does have an influence. Since the data shown in Table 1 indicate no fixation time differences between RRS and FRS, we collapsed across these two categories to obtain a single return saccade latency for saccades launched from high frequency words and one from low frequency words and then compared these means to those for non-return saccades (again collapsing across regressive and forward saccades). The resulting means were as follows: high frequency return saccade = 256 ms; low frequency return saccades = 302 ms; high frequency non-return saccades = 227 ms; and low frequency non-return saccades = 248 ms. Consistent with a great deal of other research (see Rayner, 1998 for a review of frequency effects) we found a 34 ms shorter fixation duration on high frequency than on low frequency words. More interestingly, for our present purposes, there was also a 24 ms return saccade effect for high frequency words and a 37 ms return saccade effect for low frequency words. [6]

4. Discussion

The basic inhibition of return phenomenon is a low-level covert attention effect suggesting that there is a processing cost for returning attention back to locations that have just been attended to. Likewise, oculomotor experiments in which subjects must fixate on a series of targets have demonstrated a cost associated with moving the eyes back to targets that have just been fixated (Hooge & Frens, 2000). In the context of visual search, Klein and MacInnes (1999) suggested that inhibition of return is facilitative in that it acts as a tagging mechanism so that subjects do not move their eyes back to a region that they just examined. The interesting finding reported here is that the effect also generalizes to reading. That is, we found results in reading very similar to those reported by Hooge and Frens (2000) in a more simple oculomotor task. While it is unlikely that there is any efficiency-based tagging mechanism in reading [7] (as in visual search), it apparently is the case that readers are reluctant to move their eyes back to words they've just read.

The real question is whether or not the results we obtained truly reflect an inhibition of return effect. It could be argued that the effects we observed are not really due to inhibition of return, but rather reflect some type of comprehension difficulty or breakdown. That is, perhaps readers moved their eyes back to a word that they had just fixated because they had not fully processed it or it didn't fit with their on-going discourse representation. Thus, longer fixation durations prior to returning to a previously fixated word would be due to comprehension problems rather than being a low-level inhibition of return effect. Although such an explanation may be viable, and while we readily acknowledge that we can not fully discount such an account, at the moment we suspect that it is somewhat unlikely. There are three reasons for this. First, for regressive eye movements one could just as easily argue that when a word is skipped that the reader had not fully comprehended it; in this case, fixations preceding regressions should be longer for skipped words than words just fixated. [8] So, it is difficult to know if a fixation preceding a regression should be longer when the target of the regression is a word that was just fixated or just skipped; it could work either way. Second, even if it were the case that an argument for comprehension difficulties could account for the data for RRS, it is difficult to see how such a comprehension difficulty argument could account for FRS. That is, assuming that fixations are longer preceding a return saccade than a non-return saccade because the target word wasn't fully comprehended in the first place, why would the fixation preceding a FRS also be longer than the fixation preceding a forward non-return saccade? If the reader knows on fixation n (the fixation preceding the return saccade) that there was a comprehension problem, the currently fixated word has to have been processed to such a level that the reader knows that the prior word could not be combined with the currently fixated word. Thus, fixation n might be lengthened due to comprehension difficulty. But, why would fixation $n+1$ also be lengthened in the case when the reader goes back to the word previously fixated (via a FRS) in comparison to when the eyes either fall short of that word or skip over that word on the ensuing saccade? Perhaps one could argue that it all reflects massive comprehension difficulty, but recall that we removed all instances in which the reader made a series of regressions (which typically reflect comprehension breakdown). Third, the analyses we did of fixation $n-1$ and saccade $n-1$ offered no suggestion that a global comprehension problem was influencing the data.

At the moment then, we tend to suspect that our data reflect the existence of an inhibition of return effect in reading and, therefore, they offer evidence that eye fixations during reading can be influenced by low-level oculomotor/attentional processes. We do not think that the existence of such an effect in reading means that the reader consciously keeps track of all of the places in the text where he/she has fixated. Rather, it is likely that the inhibition of return effect in reading stems from the neurophysiological system for eye movement control (Yang & McConkie, 2001). Single-cell recordings of saccade processes have established that the mechanism for initiating saccades involves the interaction of two groups of neurons in the superior colliculus; move neurons and fixate neurons (Dorris, Pare, & Munoz,

[6] In the main analysis, only the 24 subjects who provided observations in all cells contributed to the data. In this subsidiary frequency analysis, all 40 subjects who provided at least one observation were used, contributing a total of 127 data points.

[7] We think it is unlikely that there would be a tagging mechanism in reading because when comprehension breaks down readers want to go back to regions previously read. Indeed, there is evidence to suggest that readers are quite good about knowing where their comprehension processes went astray as they generally are able to make saccades back to that part of the text where their analysis went wrong (see Frazier & Rayner, 1982; Meseguer, Carreiras, & Clifton, 2002).

[8] In contemporary models of eye movements in reading, when a word is skipped, it is still processed on the preceding fixation (Reichle, Pollatsek, Fisher, & Rayner, 1998).

1997; Munoz & Wurtz, 1995). The activation of one of these groups inhibits the activity of the other, such that activation of the fixate neurons releases a tonic inhibition to the move neurons and a stable gaze, or fixation, results. The direction and amplitude of saccades are recorded contralaterally in the superior colliculus (Hooge & Frens, 2000). This vector record could be mapped into a central spatial representation or salience map in which raised thresholds provide a record of prior saccade locations (Yang & McConkie, 2001). These raised thresholds could then give rise to the inhibition of saccadic return effect by requiring additional activation of the move neurons in the superior colliculus in order to initiate a return saccade. [9] This additional activation could be provided by higher-order processes if a return saccade was needed to complete word identification, for example. Indeed, it is well-known (Rayner, 1998) that eye fixations are influenced by variables reflecting the ease or difficulty of processing a word (such as word frequency and predictability in text). In the research reported here, even though the data are at best suggestive, we did find evidence that word frequency affects the duration of a fixation preceding a return saccade. The influence of frequency is an example of higher-order cognitive processes influencing eye movement control.

The lack of interaction between frequency and return vs. non-return saccades that we observed might appear to contrast with results reported by Chasteen and Pratt (1999). In single-word lexical decision and semantic categorization tasks, they found larger inhibition of return effects for low than for high frequency words. However, in their case, the frequency of the word to which the eyes were moving was manipulated (and the dependent variable was time to make the required decision about the word, not the time to initiate a saccade). In our study, the frequency of the word from which the eyes moved was examined, and saccade latency was the dependent variable. Further research is needed to determine whether the frequency of the word to which the eyes move affects the magnitude of the return saccade effect in reading.

It is also interesting to consider the extent to which low-level oculomotor effects generalize from simple oculomotor latency tasks to the more complex task of reading. It is the case that some effects interestingly apparently carry over to reading, while others do not. One obvious effect that apparently does carry over from simple oculomotor tasks (Becker & Jürgens, 1979) to reading (Morrison, 1984; Reichle et al., 1998) is *parallel programming of saccades*. McConkie, Kerr, Reddix, and Zola (1988) found that in reading the landing position of the eyes shift as a function of the launch site of the saccade (see also Rayner, Sereno, & Raney, 1996) and suggested this was due to a *range effect* (see Vitu, 1991a, for arguments against such a range effect in reading). Another low-level oculomotor effect that may have some carry over to reading is the *global effect* or *center of gravity effect* (Findlay, 1982). Although there is variability in landing positions, readers tend to make their first fixation on a word about halfway between the beginning and the middle of a word (Deutsch & Rayner, 1999; McConkie et al., 1988; Rayner, 1979; Rayner et al., 1996; Vitu, 1991b). There has been considerable debate about the extent to which being fixated away from the center of the word results in longer fixation time on a word. For words in isolation there is a clear processing cost of roughly 20 ms per letter that the fixation location deviates from the middle of the word (O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984). However, when words are in text, although readers refixate more when their initial fixation on the word is away from the center of the word, the processing cost associated with being in the wrong place is greatly attenuated or absent (Rayner et al., 1996; Vitu, O'Regan, & Mittau, 1990).

In contrast to the low-level oculomotor effects that either carry over or partly carry over to reading (like the landing position effect just discussed), other effects do not seem to generalize from simple oculomotor tasks to reading. For example, Inhoff, Topolski, Vitu, and O'Regan (1993) found no evidence for *express saccades* in reading in the sense that there was no bimodal distribution of fixation durations (with no separate distinct peak for very short fixation durations). Likewise, Liversedge et al. (2003) found no evidence for a *gap effect* in reading: readers read just as fast when the fixated word disappeared after 60 ms as when the text was presented normally, But they did not move their eyes faster when the fixated word disappeared.

What is most interesting about a comparison between those simple oculomotor effects that seem to carry over to reading versus those that do not is the fact that the former seem to be tied more to where to move the eyes while the latter are more tied to when to move the eyes. Thus, attempts to see if express saccades and the gap

[9] Alternatively, as discussed by Hooge and Frens (2000), a saccade represented as a vector could directly inhibit its opposite vector, eliminating the need to appeal to a spatial map. This proposal would be disconfirmed if inhibition of return persists across intervening saccades. We examined our data to see whether there was any evidence for inhibition of return in the case of saccades that returned to a position that had been fixated two fixations previously. The mean fixation duration (pooling over all "2-back" forward and regressive saccades made by the 48 subjects in Groups 2 and 3) was 242 ms for return saccades, which can be compared to the mean of 232 ms for non-return saccades and 268 ms for 1-back return saccades. Unfortunately, the 2-back return saccade mean was based on only 119 observations contributed by the 48 subjects, and cannot be considered stable enough to base a clear conclusion upon. Nevertheless, it appears that the effect was attenuated in the 2-back case.

effect (which involve decisions about when to move the eyes) generalize to reading have indicated that they do not. The return saccade effect that we have observed seems to be an exception to this generalization in that it appears as an effect on when to move (though the underlying mechanism probably involves where to move).

In summary, while we can't conclusively rule out a comprehension difficulty explanation for the return saccade effects we observed, it does seem that our data are at least suggestive of the notion that readers don't like to go back to words they just read. In general then, we suspect that both low-level variables and variables reflecting lexical/discourse processing can have an influence on fixation times in reading. Of course, since the frequency of return saccades is relatively small, much of the variance in fixation times can be accounted for by lexical/discourse processing of the fixated word (Rayner, 1998; Reichle et al., 1998).

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