The effect of load on spatial attention depends on preview: Evidence from a reading study

Saeideh Ghahghaei[1], Karina J Linnell[2]

1. The Smith-Kettlewell Eye Research Institute, San Francisco, CA, USA.
2. Goldsmiths, University of London, London, UK.

Corresponding author: Saeideh Ghahghaei (saeideh@ski.org)

Address: The Smith-Kettlewell Eye Research Institute
2318 Fillmore St
San Francisco
CA, 94115
USA.

Abstract

The spatio-temporal distribution of covert attention has usually been studied under unfamiliar tasks with static viewing. It is important to extend this work to familiar tasks such as reading where sequential eye movements are made. Our previous work with reading showed that covert spatial attention around the gaze location is affected by the fixated word frequency, or the processing load exerted by the word, as early as 40 ms into the fixation. Here, we hypothesised that this early effect of frequency is only possible when the word is previewed and thus pre-processed before being fixated. We tested this hypothesis by preventing preview. We investigated the dynamics of spatial attention around the gaze location while the observer read strings of random words. The words were either always exposed (normal preview) or only exposed while being fixated (masked preview). We probed spatial attention when a target word with either high or low printed frequency – or low or high load, respectively - was fixated. The results confirmed that, early in a fixation, allocation of spatial attention 6 characters from the gaze was affected by the word's frequency but only when the word was exposed before being fixated, so that processing of the word could start before it was fixated. Our results indicate that the ongoing processing load of a word is modulated by its pre-processing and affects the dynamics of covert spatial attention around the word once it is fixated.

Key words: spatial attention, load, preview, reading, word frequency, sequential saccades.

Introduction

Reading involves sequential eye movements, saccades, to bring words into the fovea one-by-one. In addition to, and to some extent independent of, these sequential shifts of overt attention, covert spatial attention is allocated to the line of text. As a result, the processing of a word's letters can occur before it is fixated, or the word can be fully processed even without it being fixated. Spatial attention is necessary for word recognition (Waechter, Besner & Stolz, 2011) and it leads the eyes (e.g., Bryden, 1961; Deubel & Schneider, 1996; Fischer, 1999; Gersch, Kowler & Dosher, 2004; Hoffman & Subramaniam, 1995; Kowler & Blaser, 1995); this makes reading a real-world framework within which to investigate the spatio-temporal distribution of spatial attention within a dynamic processing scenario (Fischer, 1999). Furthermore, manipulating the processing demand of a word in reading (e.g., by manipulating its printed frequency) enables the investigator to influence the processing load on the reader.

The effect of load on spatial attention has been investigated mainly in static viewing conditions where it has been shown that attention is more focussed when perceptual processing load is higher (e.g., Caparos & Linnell, 2009, 2010; Lavie, 1995; Linnell & Caparos, 2011; Madrid, Lavie & Lavidora, 2011). Whether and how the focus of attention is affected by processing load over time is important for models of eye movement control in reading, as well as models of word processing, because the visibility of a given letter embedded in a line of text is suggested to be affected by (i) its distance from the gaze (which affects acuity), (ii) the number of letters or blank spaces that it is surrounded by (which affects crowding), and (iii) its proximity to the focus of attention (Grainger, Dufau & Ziegler, 2016).

In our previous work (Ghahghaei, Linnell, Fischer, Dubey & Davis, 2013), we directly investigated load effects in a more realistic task that required sequential eye movements and probed spatial attention during the course of a fixation in reading. We showed that word processing load affects the dynamics of spatial attention as early as 40 ms into a fixation when preview of the upcoming word was always available (i.e., words were not masked; Ghahghaei et l, 2013). Specifically, we examined spatial attention by measuring sensitivity around the gaze. Participants read sentences for comprehension as a primary task. In addition, they performed a secondary task which consisted of *unspeeded* discrimination of the orientation of an attentional probe - a line tilted 22.5° to the right or left of the vertical meridian. The proportion correct on probe discrimination was the measure of spatial attention. (Note that unspeeded discrimination of the orientation of a probe has previously been shown to be sensitive to the profile of attention in a task requiring sequential eye movements; Gersch, Kowler, Schnitzer & Dosher, 2008.) The probe had higher contrast than the text and occurred on the line of text, 6 characters (2 visual degrees) to the left or right of the gaze location. It occurred with different temporal onsets from the start of the first fixation on the fixated word. The printed frequency of target words was modulated to be either high or low, resulting in low or high processing load for the fixated target, respectively. Our results showed that 40 ms into a fixation, there was an effect of the frequency of the fixated word on attention which disappeared by 110 ms into a fixation. This effect was significant 6 characters to the left (but not right) of the gaze location. This effect of frequency was only observed on the left side of the gaze presumably because of the asymmetry in the extent of the perceptual span; the perceptual span is a span within which useful information can be extracted and it extends roughly 5 characters to the left and 14 characters to the right of the gaze location in reading English texts for comprehension (McConkie & Rayner, 1975). This span is attentional rather than visual given that its direction depends on the direction of reading (e.g., Pollatsek, Bolozky, Well & Rayner, 1981) and it cannot be explained by visual span (e.g., Legge, Cheung, Yu, Chung, Lee & Owens, 2007) or crowding (e.g., Ghahghaei & Walker, 2016). In this situation, where less spatial attention is allocated to the left of the gaze than to the right of it, probes occurring on the left should be more sensitive to any effects of word frequency.

Ghahghaei et al (2013) showed that the processing of the fixated word exerts a load on spatial attention mechanisms such that spatial attention was more focused around the gaze when the fixated word was low rather than high in frequency. There could be two different ways that the load exerted by the fixated word is related to its processing. On the one hand, it could be that the word's load is constant over the course of the fixation and depends on the word's overall processing demand. On the other hand, it is possible that the word's load varies over time and depends on the moment-to-moment processing demand that it exerts. If the former is the case then, throughout a fixation, spatial attention should be focussed more on a low- rather than a high-frequency word, regardless of how advanced the pre-processing of the word is before it is fixated. If the latter is the case then, early in a fixation, attention should be focussed more on a low- rather than a high-frequency word only if the word is sufficiently pre-processed before being fixated. An effect of pre-processing is in theory possible because information that is obtained during word preview has been shown to be integrated across the saccade to the word (e.g., Inhoff, Starr & Shindler, 2000; Rayner & Clifton, 2009).

In addition to models of eye movement control in reading, other models of eye movement control in tasks like scene processing or visual search can benefit from including effects of load on the focus of attention. To build their visibility map, these models normally use a visual field that is constrained by visual acuity but not the availability of spatial attention during the course of the fixation (e.g., Ghahghaei & Verghese, 2015; Itti, Rees & Tsotsos, 2005; Najemnik & Geisler, 2005; Renninger, Verghese & Coughlan, 2007). These models will benefit from considering the availability of spatial attention - as it depends on the time elapsed since the last saccade in addition to when the upcoming saccade is made- and the ongoing processing load.

In the work reported here, we asked if an effect of frequency on spatial attention depends on whether the word has been pre-processed before being fixated. We did so by manipulating the validity of preview and the frequency of target words. In daily life experiences, provided that vision is normal, the amount of preview will vary depending on the task and the quality of parafoveal visual information. Here, we look at two ends of the continuum in a reading task: when letter identity information for preview is completely available (normal preview) and when it is completely denied (masked preview).

The validity of preview in reading is usually modulated using a boundary paradigm (Rayner, 1975a, 1975b). In this paradigm, words are masked before being fixated and unmasked upon the saccade to the word. Preview of the word is (i) valid (i.e., normal) if the mask is identical to the word (i.e., no mask) or (ii) invalid if the mask is different. Having a normal preview decreases the duration of fixations (Fitzsimmons & Drieghe, 2011) and increases the speed of reading (Rayner, Liversedge & White, 2006) indicating that the reader benefits from previewing words (Dodge, 1907; Rayner, 1975 a,b). Here, instead of using the boundary paradigm to manipulate preview, we used the one-word moving-window paradigm. In the one-word moving-window paradigm, at any given moment, only letters of the fixated word are exposed and letters of all other words are masked (although blank spaces are preserved; Figure 1.) We used the moving-window paradigm instead of the boundary paradigm in order to ensure that all words on both the left and right sides of the fixated word (but not the fixated word itself), were masked when preview was masked, so that lexical information could be extracted only from the fixated word but not the neighbouring words. Two groups of participants performed the task. For one group preview was manipulated to be masked (using the one-word moving-window paradigm). For the other group, there was no manipulation of preview and words were never masked.

We probed spatial attention using the same method as in Ghahghaei et al. (2013). The primary task was to read, in silence, one string of random words at a time (as opposed to reading one sentence at a time for comprehension, as in Ghahghaei et al., 2013; see the Method section for more details). We chose a task involving reading strings of words instead of sentences because we wanted to see whether effects of word frequency on spatial attention remain when no higher-level sentence context is provided and we wanted to see if there are word-frequency effects on both sides of the gaze in string reading, rather than only on the left side as in reading. It is shown that in reading strings of words compared to sentences, the perceptual span is smaller on the right side (in the direction of reading) and thus the span is less asymmetric around the gaze (Häikiö, Bertram, Hyönä & Niemi , 2009; Inhoff, Pollatsek, Posner & Rayner, 1989). Finally, we chose strings because, given the resolution of our eye-tracker, it is difficult to use the one-word moving-window paradigm when stimuli contain short words and articles, as in a sentence.

The secondary task was unspeeded discrimination of the orientation of the probe (a tilted line that occurred six characters to the left or right of the gaze location). As in Ghahghaei et al. (2013), the accuracy of the discrimination of the probe was the measure of the allocation of spatial attention at the location of the probe. Similar to Ghahghaei et al. (2013), there was a target word in each string of words, unbeknown to the reader, and the frequency of the target word was either high or low. We probed spatial attention six characters to the left or right of the gaze location (i.e., two visual degrees from the gaze) when the target word was fixated for the first time. The probe-onset occurred either 10 ms or 40 ms from the start of the first fixation on the target word. In Ghahghaei et al. (2013), frequency effects were observed when probes occurred as early as 40 ms into a fixation, and here we also included the even earlier probe onset of 10 ms to see whether word frequency can affect the profile of attention as early as 10 ms into a fixation.

2. Method

2.1. Participants

Fifteen native monolingual English-speakers participated in the normal-preview condition (10 females). Another group of 15 native monolingual English-speakers participated in the masked-preview condition (9 females). Participants were all between 18 and 30 years old and had normal or corrected-to-normal vision. They were non-dyslexic skilled readers (who self-reported as college students or graduates from college). Ethics approval was granted by the Smith-Kettlewell Eye Research Institute institutional review board. Informed consent was obtained from all participants at the beginning of their first session. The study was conducted in accordance with the Declaration of Helsinki. Participants received money in return for their participation.

2.2. Apparatus

Word stimuli were displayed on a 21W ViewSonic G225f monitor. Eye movements were recorded using an EyeLink 1000 Tower Mount eyetracker. A Microsoft gamepad was used to log participants' responses.

2.3. Stimuli

Each word string was displayed in grey (the luminance of the text was 7.98 cd/m^2) in 15-point monospaced Courier New Regular font, left-aligned on an otherwise black display. Each character, including its boundary, subtended 0.37° horizontally. Probes were oblique lines whose top end was oriented +22.5° or -22.5° from the vertical axis. Probe width and height were 0.25° and 0.57° respectively. The probe was brighter than the text and was briefly, for 30 ms, superimposed on a character in the text (6 characters to the left or right of the gaze location).

The word stimuli were nouns (not verbs, adverbs or articles), 5-8 characters in length. Words were presented in strings and were not predictable from the previous words in the string. There was no repetition of words in a string of words. Each string contained a target word. The length of the target word was 6, 7 or 8 characters. The printed frequency of the target word was manipulated to be either high or low (see Table 1). Frequencies of target words were measured using the written portion of the British National Corpus (BNC), a 100-million-word balanced corpus of British English. The target words used in this study were a subset of the target words used in Ghahghaei et al (2013). The word that preceded the target word was always a high-frequency word. Target words were never used as non-target words in any string.

Sample strings of words with either a low- or high-frequency target word are shown in (a) and (b), respectively. Note that in each string of words, the target word is italicised only for presentation purposes.

(a) North biases dealer sweets *mishap* handle music mileage wreck.

(b) Human licence queen trouble *mission* debate signal folder penny.

There was a set of 176 strings of words containing a high-frequency target word and another set of 176 strings of words containing a low-frequency target words. The stimulus set was not item-based.

In the masked-preview condition, at each point in time, only those letters that were embedded in the fixated word were exposed. All other letters were masked by random consonants. Consonants occurred with the same frequency that consonant letters occur in English texts. Word boundaries were preserved (see Figure 1a).

	Word frequency	Average	Minimum	Maximum
Log word frequency	Low	0.99	-4.61	2.66
	High	4.45	2.85	6.08

Table 1. Log frequencies of high- and low-frequency words.

2.4. Design

Participants read strings of words that were randomly chosen and were not related to each other. To ensure that the effective frequency of low-frequency words was equal for both normal and masked-preview conditions, two different groups viewed the word in either mask and no-mask condition. Preview was therefore masked for one group and normal for another group. Each string of words contained a target word. The target word was either low or high in frequency. The probe occurred with a temporal onset of 10 ms or 40 ms from the beginning of the first fixation on the target word with a spatial offset of -6 or +6 characters from the gaze location. Thus, the study was a 2 (preview: masked or normal) X 2 (frequency of the target word: high or low) X 2 (spatial offset of the probe: 6 characters to the left or right) X 2 (temporal onset of the probe: 10 ms or 40 ms) design. Preview was a between-subject factor. For each of the eight combinations of the within-subject experimental factors, there were 44 samples (strings of words). For each participant, a list of 352 strings of words was made with a randomized order of the within-subject experimental conditions. Each participant was presented with a different list. The study was conducted in three sessions, preferably on two separate days. If separate days were not possible, participants had at least a one-hour break between sessions.

2.5. Procedure

For the primary task, each participant read strings of words in silence (see Figure 1). One string of words was presented on the screen at a time. Strings of words were left-aligned. In 25% of the trials, participants answered an *identification* question *after* they read the string of words; on these trials, they were asked whether or not a specific word was presented in the string of words they had just read. A verbal response (Yes/No) was required to this question and the experimenter logged the response. Participants received audio feedback on the identification task. If the to-be-identified word was indeed in the string, it was always chosen from the first or the last two words in the string. Participants were not informed about this and as far as they knew all words in the string could potentially be the presented for the identification question. None of the participants reported noticing that the identification words were from the first or last two words. The target word was never within the first or the last two words; therefore, the to-be-identified word was never the target word. Participants were frequently reminded to read with their normal speed of reading, that is, neither very slow nor very fast.

The Eyelink calibration routine was performed every twenty trials or as needed. A drift correction was performed at the beginning of each trial. Gaze-contingent probes were presented when the eyes landed on the target word in each string of words. The secondary task was to discriminate the orientation of the probe after participants had read the string of words and the string had disappeared but before the identification question. Participants were informed that the probe only occurred around the gaze and not at the gaze location.

At the beginning of the first session, participants received practice trials on which, for the primary task, they read a set of ten, followed by a set of thirty, *sentences* for *comprehension*. All the target words in these sentences were high in frequency. In these practice trials, the probe occurred 6 characters either to the left or right of the gaze with a temporal onset of 40 ms. To avoid ceiling or floor effects, the probe luminance was adjusted for each participant during the practice block to maintain about 75% accuracy on the probe

Figure 1. A schematic representation of one trial in the masked-preview condition. a) Here the target word (trench) was low in frequency. Words were masked when not fixated. The probe occurred 6 characters from the gaze (here, on the right side) location, 40 ms after the beginning of the first fixation on the target word. The top end of the probe pointed either to the left or right (here, right). The probe disappeared after 30 ms. The string disappeared when the gaze passed an invisible boundary to the right of the last letter in the string or when the eye fixated the last word for 600 ms. In the normal-preview condition, the words were always exposed. b) The participant performed an unspeeded 2-AFC discrimination task (using a manual response) for the orientation of the probe.(c) Finally, the participant

answered (with an oral response) an identification (Yes/No) question about the string he/she had just read.

(with a mean luminance of 14.72 cd/m^2 across participants). After the luminance of the probe was adjusted, the participant received a third block of practice in which for the primary task she/he read a set of twenty *strings of words* followed by an identification question after each string. For the masked-preview condition, participants were presented with another set of practice trials, including twenty strings of words with a masked preview in a one-word moving-window paradigm (see Figure 1). Thus, both normal-preview and masked-preview groups performed the first three blocks of the practice trials in which preview was normal; the masked-preview group also performed one extra practice block with a masked preview. We did not ask participants in the masked-preview group whether they were aware of the gaze-contingent display change as a result of the gaze-contingent masking/unmasking of letters when performing the reading task; however, according to their self-report, all participants found the reading task easy. Target words presented in the practice blocks were not used in the main blocks.

3. Results

Participants who did not have more than 90% accuracy on the identification questions were excluded (two from each group). For the remaining participants, trials were included if (i) the duration of the first fixation on the target was at least 100 ms, (ii) the probe occurred during this fixation and (iii) this fixation was not followed by a backward saccade. For the normal-preview group, the average number of accepted trials per condition per participant was 35.6 (*SEM* = 0.6) samples (out of a total of 44). For the masked-preview group, the average number of accepted trials per condition per participant was 36.8 (*SEM* = 0.4) samples (out of a total of 44). We did not control for blinks, although reading each string of words took less than 3 seconds and participants were asked to blink between and not within trials; thus the chance of a blink within a trial was low.

In what follows, we first show that reading, as indexed by the processing of words at lexical levels, was not disturbed by the probe: specifically, effects of word frequency on fixation durations on target words were preserved. Then, we show that our preview manipulation was effective by showing that the speed of reading decreased when preview was masked compared to when it was normal. Then, we look at the effects of preview and word frequency on the dynamics of spatial attention around the gaze location as revealed by the accuracy of probe discrimination.

We ran a 2 (preview: normal and masked) X 2 (word frequency: low and high) X 2 (spatial offset: -6 and +6) X 2 (temporal onset: 10 ms and 40 ms) mixed-design ANOVA, with preview as a between-subject variable, on the duration of first fixations on target words and on accuracy rates on discriminating the probe. To investigate an effect of preview on the speed of reading we ran a *t*-test comparing the speed of reading for the normal-preview group and the masked-preview group with preview as a between-subject factor.

3.1. Fixation Durations

Table 2 illustrates the average durations of first fixations on target words. Most importantly, there was an effect of word frequency ($F(1,24) = 16.11$, $p = 0.001$) on fixation durations: The average duration of the first fixation was 447 ms (*SEM* = 12) and 430 ms (*SEM* = 12), respectively, for low- and high-frequency words. The effect of word frequency confirmed that words were processed at lexical levels.

The durations of first fixations on target words were longer when preview was masked (*mean* = 446 ms, *SEM* = 16) than normal (*mean* = 432 ms, *SEM* = 20) but the difference was not significant ($F(1,24) = 0.36$, $p > 0.05$). There was an effect of spatial offset ($F(1,24) = 56.12$, $p = 0.001$) on fixations: The average duration of the first fixation was 484 ms (*SEM* = 15) and 393 ms (*SEM* = 10), respectively, when the probe occurred 6 characters to the left or right of the gaze location. The effect of the spatial offset of the probe is consistent with findings that an abrupt-onset stimulus interferes less with saccade programming when it occurs in the direction of the saccade (e.g., Findley & Walker, 1999; Ghahghaei et al., 2013; Walker, Deubel, Schneider & Findlay, 1997).

Spatial offset (6 characters)		Left				Right			
Temporal onset (ms)		10		40		10		40	
Word frequency		Low	High	Low	High	Low	High	Low	High
Preview	normal	467	449	498	485	392	381	393	392
		21	*22*	*25*	*25*	*14*	*15*	*18*	*15*
	masked	474	463	536	506	413	388	409	381
		21	*22*	*25*	*25*	*14*	*15*	*18*	*15*

Table 2. Average duration of first fixations on target words. The average duration of the first fixations on target words (in ms) are shown for normal- and masked-preview, low- and high-frequency words and for different spatial and temporal onsets of the probe. Standard errors of means are shown in italics.

In addition, there was an interaction between spatial offset and temporal onset ($F(1,24) = 19.19$, $p = 0.001$): For probes occurring on the right side of the gaze, the temporal onset of the probe did not significantly affect the duration of the first fixation on target words ($p > 0.05$). For probes occurring on the left side of the gaze location, however, the average fixation durations were 463 ms ($SEM = 14$) and 506 ms ($SEM = 17$) for temporal onsets of 10 ms and 40 ms, respectively, and the difference was significant ($F(1,24) = 34.47$, $p = 0.001$). Thus, probes occurring on the left side of the gaze delayed the upcoming saccade even more when they occurred later in a fixation and presumably closer to when the programming of the upcoming saccade was about to start (Becker & Jürgens, 1979).

3.2. The speed of reading

The speed of reading was calculated as the ratio of 'the distance of the critical fixation location from the beginning of the string of words in characters' and 'the time elapsed from the beginning of the trail until the target word was fixated'. Thus, it was not affected by the occurrence of the probe. Reading was faster for the normal-preview (*mean* = 16.94 characters per second; *SEM* = 1.21) than the masked-preview (*mean* = 15.35 characters per second; *SEM* = 0.44) condition but the difference was not significant ($p = 0.22$). Nevertheless, the speed of reading was reduced by almost 10 % when preview was masked. Thus, we conclude that participants did benefit from having a normal preview of the words before fixating them.

3.3. Performance on the probe

There was no main effect of preview ($F(1,24) = 0.06$, $p > 0.05$). There was a main effect of spatial offset ($F(1,24) = 43.23$, $p = 0.001$): The average accuracy was 66 % (*SEM* = 1.5) and 76 % (*SEM* = 1.2) for probes occurring 6 characters to the left or right of the gaze location, respectively, confirming that the allocation of spatial attention 6 characters from the gaze location was larger in the direction of reading than in the opposite direction. Note that the relative allocation of attention on the left and right side of the gaze is probed only 10 ms and 40 ms into fixations. The extent/strength of the attentional span across the course of the fixation may vary, resulting in different asymmetries across the gaze location at different points in time (Ghahghaei et al, 2013). There was an effect of temporal onset ($F(1,24) = 142.88$, $p = 0.001$): The average accuracy was 64 % (*SEM* =1.2) and 77 % (*SEM* = 1.2) for temporal onsets of 10 ms and 40 ms, respectively, confirming that the allocation of spatial attention around fixation increased over time. Effects of spatial offset and temporal onset were in line with the observed effects in Ghahghaei et al (2013) where the task was to read sentences for comprehension.

There was an unexpected interaction between temporal onset and preview ($F(1,24) = 9.27$, $p = 0.006$). The average difference between probe discrimination for probe-onsets of 10 ms and 40 ms was 11 % (*SEM* = 2.9) for the masked-preview condition and 16 % (*SEM* = 4.9) for the normal-preview condition (Figure 2a). Thus, although the accuracy on probe discrimination increased with the temporal onset of the probe ($p < 0.001$) for both preview conditions, it did so faster for the normal- than masked-preview condition. This is compatible with the speed of increase in the allocation of spatial attention around fixation being larger for the normal- than the masked-preview group. We looked at the change in allocation of spatial attention from 10ms to 40ms into the fixation in the parafovea with or without normal preview. A post-hoc t-test showed no significant difference in this change of allocation of spatial attention between the normal and masked-preview conditions. Nevertheless, the unexpected significant interaction is compatible with a processing load that varies and that depends on moment-to-moment changes in the stage of processing of the fixated word. We note that manipulation of preview affects access to visual information of the word's letters and thus affects the timecourse of word processing relative to the beginning of the first fixation on the word. A significant interaction thus shows that the mechanisms that are involved in the dynamics of spatial attention when making sequential saccades (such as in reading) are affected by mechanisms involved in word processing. It is however possible that the gaze-contingent display change in the masked-preview condition affected spatial attention and slowed down the release of attentional resources to the parafoveal region.

There was an effect of word frequency ($F(1,24) = 8.59$, $p = 0.007$) on probe discrimination: The average accuracy was 69 % (*SEM* = 1.2) for low- and 72 % (*SEM* = 1) for high-frequency words. Most importantly, the effect of word frequency interacted with preview ($F(1,24) = 7.99$, $p = 0.009$; Figure 2b). To investigate this interaction, we looked at effects of word frequency on probe discrimination accuracy separately for each preview group. Planned paired-samples *t*-tests show an effect of word frequency when preview was normal ($t(-3.86)$, $p = 0.002$) but no effect of word frequency when preview was masked ($t(12) = 0.18$, $p = 0.86$). We argue that, when normal preview was denied, processing of the word was not sufficiently advanced to reveal an effect of frequency on attention early in a fixation (at temporal onsets of 10 ms and 40 ms); therefore, the interaction also represents the timecourse of frequency effects on the focus of spatial attention, although a 3-way interaction with temporal onset was not significant ($p > 0.05$). In sum, the interaction between preview and word frequency early in a fixation showed that the frequency of the fixated word affected the allocation of spatial attention around it only when the word was previewed and received some pre-processing before being fixated; thus the previewed word was at a more advanced stage of processing at the time of the probe.

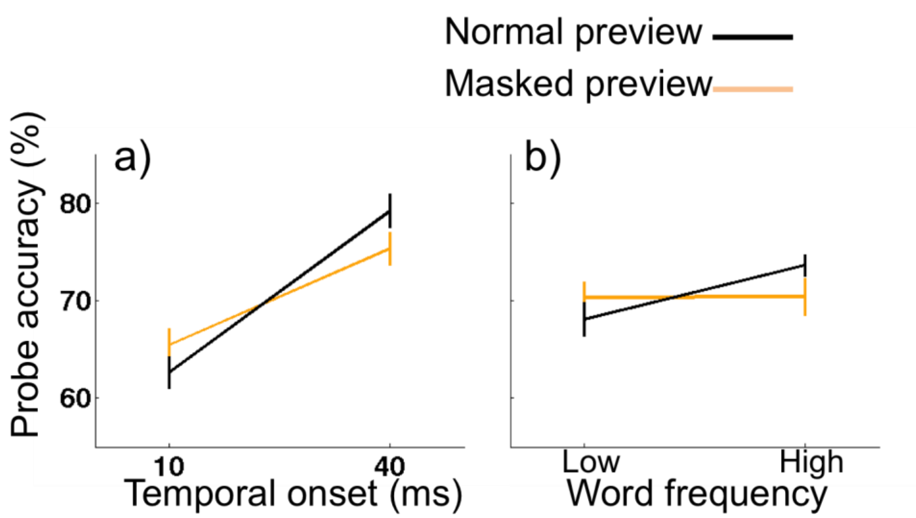

Figure 2. Preview interacted with (a) temporal onset and (b) word frequency. The average percentage accuracies for probe discrimination are shown for when preview was normal (black lines) and masked (orange lines). a) Probe discrimination accuracy increased going from the temporal onset of 10 ms to 40 ms for both preview groups. b) Probe discrimination accuracy was better when high- rather than low-frequency words were fixated, but only when preview was normal. Error bars show one standard error of the mean (SEM).

3.4. Was there a task trade-off?

The previous conclusion rests however on the participants in our study having complied with our request for them to prioritize the reading task over the probe discrimination task. If task priority was preserved, then performance on the probe was indeed a direct measure of spatial attention. However, human participants usually want to perform well on any task that they participate in. In our study, although we emphasised the reading task, and indeed only provided feedback for this task, participants probably wanted to perform well on both reading and probe discrimination tasks. If task priorities were not preserved, then better performance on the probe would result in poorer performance on the reading task, that is, longer fixation durations.

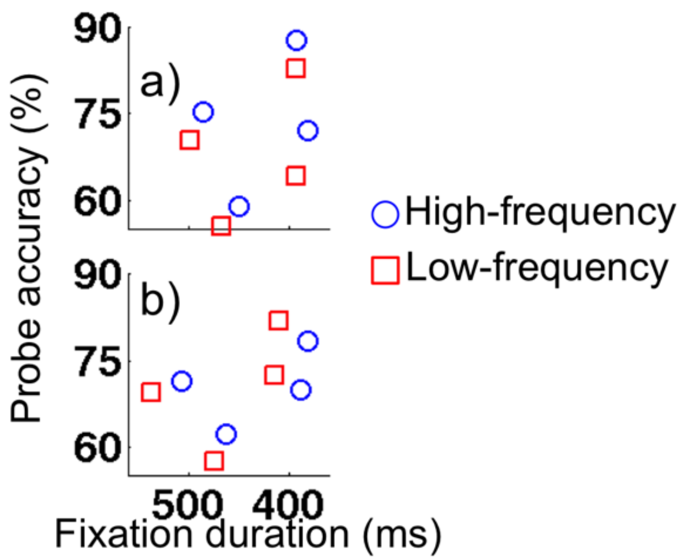

Figure 3. AOC curves. The figure shows average probe discrimination accuracy as a function of the average duration of first fixations on target words for the normal- (a) and masked- (b) preview groups. Blue/red marks represent performance for when the fixated word was high/low in frequency respectively. Data are collapsed across spatial offset (-6 or +6 characters from the gaze) and temporal onset (10 ms or 40 ms) of probes. Note that the x-axis is descending and the y-axis is ascending.

To ensure that task priorities were preserved, we plotted the Attentional Operating Characteristic curve (AOC; Sperling & Melchner, 1978) for both normal- and masked-preview conditions (see Figures 3a and b respectively). The AOC curve did not show any evidence of a trade-off between the primary task (i.e., reading) and the secondary task (i.e., discriminating the probe): the average fixation durations were shorter when the average accuracy on probe discrimination was higher; this was regardless of preview, word frequency or when/where the probe occurred. Thus, when the observer performed better on the probe discrimination task they did not perform worse on the reading task. Therefore, we conclude that task priority was preserved and that our conclusions about spatial attention based on probe discrimination are warranted.

4. Discussion

Ghahghaei et al. (2013) showed that, when reading sentences for comprehension, word frequency affects spatial attention around the gaze location early during the first fixation on the word. Using the same method, but removing contextual information by changing the task to one of reading strings of random words (with presumably a smaller and less asymmetric perceptual span), we again showed an effect of frequency on spatial attention around the gaze location early in a fixation. Indeed, this effect was observed as early as 10 ms - and not just 40 ms into a fixation - and then on both sides of the gaze. We tested the hypothesis that an effect of word frequency early during a fixation was the result of the word receiving some pre-processing before being fixated and it exerting a varying processing load over time. Indeed, our results confirmed this hypothesis: there was no effect of word frequency on spatial attention, early in a fixation, when preview of the fixated word was masked so that the word could not be pre-processed before being fixated.

4.1. Effect of preview

Not having a preview slowed down the speed of reading and prolonged the duration of first fixations on target words. Although the effects were not significant, they were in the expected direction.

This preview effect was in spite of the fact that for more demanding tasks, such as reading strings of random words as opposed to sentences, the perceptual span in reading is smaller and this reduces the preview benefit (Häikiö, Bertram, Hyönä & Niemi , 2009; Inhoff, Pollatsek, Posner & Rayner, 1989). Nevertheless, the results confirmed that when reading strings of random words participants did benefit from previewing the words before fixating on them.

Most importantly, when preview was normal, but not when it was masked, early during a fixation, the allocation of spatial attention in the parafovea (6 characters from the gaze location) was affected by the frequency of the fixated word: the attentional allocation was larger when the fixated word was high rather than low in frequency. Our results replicated our findings on the effect of the frequency of fixated words in *sentence reading* on parafoveal spatial attention (Ghahghaei et al., 2013) even when the reading task involved unrelated strings of words. This suggests that our earlier results can be generalized to other reading tasks. In addition, the effect of word frequency was observed on both sides of the gaze location in reading strings of random words, whereas it was observed only on the left side of the gaze location in reading sentences, as predicted by the finding that the perceptual span is less asymmetric when the reading task is more demanding (Häikiö, Bertram, Hyönä & Niemi, 2009; Inhoff, Pollatsek, Posner & Rayner, 1989).

When preview was masked, in contrast, early during a fixation the allocation of spatial attention six characters from the gaze location was not affected by the frequency of the fixated word. We conclude that, when preview is masked, the processing of the word is delayed and, as a result, early during the first fixation on the word it has not reached levels corresponding to word frequency; as a result, spatial attention is not yet affected by word frequency. It is important to remember that we only probed spatial attention as late as 40 ms into a fixation; later than 40 ms during the fixation, it is possible that word frequency affects spatial attention even in the absence of preview. In Ghahghaei et al (2013), when participants read sentences for comprehension, the focus of spatial attention around the gaze was modulated by the word frequency up to 110 ms into the fixation (a later effect of word frequency appeared 180 ms into the fixation and 6 characters to the right of the gaze when attention presumably oriented towards the next word but this effect is outside the scope of the current work).

4.2 What did the probe reveal?

Our paradigm, measures the dynamics of spatial attention and, more specifically, it measures sensitivity. Because here we only probed at one distance (6 characters to the left or right of fixation), our results cannot reveal the absolute extent of the perceptual span; rather, they reveal the *relative strength* of the span on the right and left side of the gaze over time and how this is affected by higher level lexical processing of the fixated word. The extent (and presumably, the strength) of the perceptual span around the gaze depends on what information one is interested in. For example, the extent of the span is about 15 characters to the right side of the gaze for low spatial frequency information such as word boundaries. However, the extent of the span shrinks to only 8 characters to the right of the gaze if letter identity is considered. Given the nature of our probe, an abrupt onset high contrast tilted line, it is very possible that it taps into a wider perceptual span than that indexed using letter identity.

The nature of the secondary task and the identity and arrangement of the probe also affects the profile of attention that can be revealed. In Fischer's (1999) study, a similar dual task was used to measure the profile of attention around the gaze: reading was the primary task and probe detection the secondary task. The probe was an abrupt-onset asterisk that briefly appeared on the upper side of a letter (not overlapping with the letter). Using this probe, Fischer failed to reveal the asymmetric profile of spatial attention around the gaze. One could argue that, in that study, the written text and the probe tapped into different perceptual analysers (Sutherland, 1959; Treisman, 1969). In our study, on the other hand, the probe was a tilted line superimposed on a letter; there are letters in English script that are composed of titled lines, for example, 'X' and 'V'. Thus, our probe shared the same spatial location as the letter on which it occurred, and its orientation, colour and size made it a common element belonging to the set of features defining English script. Therefore, the probe tapped into a subset of the set of analysers that operate on extracting letter information in English script (see e.g., figure 1 in Treisman, 1969). Thus, we argue that our paradigm did indeed reveal the dynamics of spatial attention allocated to the line of text in reading.

4.3. Contribution to the perceptual load literature

Under static fixed-viewing conditions, several studies have shown that spatial attention is more focused on a stimulus when the perceptual load of the stimulus is higher (e.g., Brand-D'Abrescia & Lavie, 2007; Caparos & Linnell, 2009, 2010; Eriksen & St. James, 1986; Lavie, 1995;

Lavie & Tsal, 1994; Linnell & Caparos, 2011; Parks, Hilimire & Corballis, 2011). These studies have mostly used letter-based (e.g., word/nonword) stimuli (e.g., see Madrid, Lavie, & Lavidor, 2010). One could argue that words and non-words fall on a continuum axis in which high-frequency words are ‘more like words’ and low-frequency words are ‘more like non-words’. If the observed effect of word frequency on the focus of spatial attention in Ghahghaei et al (2013) is merely due to strings of letters being perceptually easier to process when they form a high-frequency word, then the effect of word frequency on the focus of spatial attention should not depend on how much pre-processing the word receives, or whether or not there is preview. The work reported here showed that this was not the case: the effect of frequency was only observed when preview was normal.

We believe that the application of our results is not limited to word stimuli. We argue that, in any task, the moment-to-moment processing load - as it is affected by (i) task requirements, (ii) the load of the fixated stimulus, and (iii) how much pre-processing the fixated stimulus receives before being fixated - affects the dynamics of spatial attention around the gaze location; this in turn affects how much pre-processing the subsequent, to-be-fixated target receives. Thus, processing of parafoveal visual information at any given moment depends not only on the load of the fixated stimuli but also on the history of the processing load up to that moment.

4.4. Contribution to the reading literature

Reingold, Reichle, Glaholt and Sheridan (2012) used a survival analysis to investigate how the validity of preview affects frequency effects on the duration of first fixations: for each value between 0 and 600 ms (with a step of 1 ms), they calculated the percentage of fixations that ‘survived’, or were longer than this value, for each participant. Then, for each value between 0 and 600 ms, they averaged the number over all participants. They plotted the resulting survival percentage curves as a function of the duration of first fixations, both for when the fixated target word was high in frequency and for when it was low in frequency. When the preview of the target word was normal (i.e., valid), the survival curves for low- and high-frequency words diverged at about 145 ms. When preview was masked, on the other hand, the survival curves diverged only at about 256 ms. If saccade planning takes about 150 ms or so, Reingold et al.'s (2012) finding means that, with a normal preview, frequency information was available to the saccade programming /execution mechanisms early in the fixation. However, with a masked preview, frequency information was not available when the word was fixated for the first time and only became available to the saccade programming /execution mechanisms halfway through the fixation. Our results add to theirs and show that, early in a fixation, word frequency information is available only when a normal preview is available, not only to affect saccade programming/execution mechanisms but also to affect the allocation of spatial attention.

Specifically, an implication of our results is that an abnormality in the allocation of spatial attention can affect the quality of reading. Temporal and spatial abnormalities in attentional mechanisms are reported in dyslexics (e.g., Visser, Boden & Giaschi, 2004). Indeed, in some groups of dyslexics, the focus of spatial attention is reported to be wider than in normal readers (Rayner, Murphy, Henderson and Pollatsek, 1989; Montani, Facoetti & Zorzi, 2014). A wider focus might result in the allocation of spatial attention to non-fixated targets so that the word to be fixated next may receive a good amount of preview processing at a point when the fixated word itself has not yet received sufficient processing. This may interrupt the correct order in which words are processed and contribute to documented disruptions in reading.

4.5. Contribution to models of eye movement control and attention in reading

Our results on the effects of word frequency and preview on spatial attention are also important for models of spatial and/or lexical attention in reading. Spatial attention is known to be necessary for word recognition under static viewing conditions (Waechter et al., 2011). However, it is important for a better understanding of word processing in real-life situations to map the involvement of spatial attention when sequential saccades are made. We showed that the moment-to-moment processing load of the fixated word modulates the allocation of spatial attention around the gaze location (six characters away from the gaze) in the presence of eye movements. Models of word processing in reading (e.g., Coltheart, Rastle, Perry, Langdon &

Ziegler, 2001) and cognitive models of eye movement planning in reading (e.g., the E-Z Reader model: Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003, or the SWIFT model: Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005; Laubrock, Kliegl & Engbert, 2006; Nuthman & Engbert, 2009; Richter, Engbert & Kliegl, 2005) can benefit from our results showing that word processing at lexicon levels (i.e., word processing stages related to word frequency) affects covert spatial attention. Spatial attention then in turn modulates the selection of lower-level visual information processing.

It is important to reemphasize that the probe in our study measured spatial attention rather than lexical attention. The availability of spatial attention at a location (e.g., 6 characters to the left or right of the gaze) does not necessarily mean that the word that is in that location should be processed at the lexical level. Thus, our result does not distinguish between models that assume only one word at a time can be processed at lexical level (such as E-Z Reader which assumes a spotlight model of attention) and models that assume that more than one word at a time can be processed at lexical levels (such as SWIFT which assumes a zoom lens model of attention). Our results on the dynamics of spatial attention can be used by both models at the level of the availability of spatial attention: the spotlight (in the case of the E-Z Reader model) or the zoom lens (in the case of the SWIFT model) of attention is dynamic, and its extent changes over time depending on the processing demand of the objects that are being processed.

Other models of eye movement control and scene processing (both bottom-up or top-down) can benefit from our findings too. To build their visibility map, these models usually use a visual field that is only constrained by visual acuity. Our findings show that, after a saccade, the focus of spatial attention widens over time depending on the moment-to-moment processing load. This affects the amount of processing that non-foveated objects receive which in turn has implications for how the next saccadic target is chosen.

5. Conclusion

Using the real-life task of reading, we have shown that the dynamics of spatial attention around the gaze location (early in a fixation) are affected by how much a fixated target word has been processed covertly before being fixated. Our results suggest that the load of the fixated word depends from moment to moment on its current processing stage which depends, in turn, on its history of processing. The moment-to-moment processing load of the fixated word modulates the allocation of spatial attention around the gaze dynamically: more spatial attentional resources are allocated to the parafoveal region whenever the fixated word exerts a lower processing load.

6. Acknowledgement

We would like to thank Dr Laura Walker and Dr Preeti Verghese and the Smith-Kettlewell Eye Research institute. We would also like to thank Dr Anna Ma-Wyatt for her feedback on an earlier version of the manuscript and Dr Fernanda Ferreira and Dr John Henderson for their useful comments. This word was partially funded by a Goldsmiths' International Student Scholarship to SG.

7. References

Bundesen, C. (1998). A computational theory of visual attention. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *353*(1373), 1271-1281.

Brand-D'Abrescia, M., Lavie, N. (2007). Distractor effects during processing of words under load. *Psychonomic Bulletin & Review*, *14* (6) 1153–1157.

Bryden, M. P. (1961). The role of post-exposural eye movements in tachistoscopic perception. *Canadian Journal of Psychology/Revue canadienne de psychologie,15*(4), 220-225. doi: 10.1037/h0083445.

Caparos, S., Linnell, K., J. (2009). The interacting effect of load and space on visual selective attention. *Visual Cognition*, *17*(8), 1217-1227.

Caparos, S., Linnell, K., J. (2010).The spatial focus of attention is controlled at perceptual and cognitive levels. . *Journal of Experimental Psychology: Human, Perception & Performance, 36*(5):1080-107.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: a dual route cascaded model of visual word recognition and reading aloud.*Psychological review*, *108*(1), 204.

Deubel, H., & Schneider, W. (1996). Saccade target selection and object recognition: evidence for a common attentional mechanism. *Vision Research*, *36*(12), 1827-1837.

Dodge, R. (1907). An experimental study of visual fixation. *Psychological Review Monograph Supplement, 4*, iv – 92.

Engbert, R., Longtin, A., & Kliegl, R. (2002). A dynamical model of saccade generation in reading based on spatially distributed lexical processing. *Vision Research*. *42*, 621- 636.

Engbert, R., Nuthmann, A., Richter, E., & Kliegl, R. (2005).SWIFT: A dynamical model of saccade generation during reading. *Psychological Review*, 112, 777-813.

Ericsen, C. W. & St James, J. D. (1986). Visual attention withon and around the field of focal attention: A zoom lens model. *Perception & Psychophysics*, *40 (4)*, 225-250.

Findlay, J. M., & Walker, R. (1999). A model of saccade generation based on parallel processing and competitive inhibition. *Behavioural & Brain Sciences*, 22, 661–674.

Fischer, M. H. (1999). An investigation of attention allocation during sequential eye movement tasks. *Quarterly Journal of Experimental Psychology A, 52*(3), 649-677.

Fitzsimmons, G., & Drieghe, D. (2011). The influence of number of syllables on word skipping during reading. *Psychonomic Bulletin & Review, 18*, 736–741.

Ghahghaei, S., Linnell, K. J., Fischer, M. H., Dubey, A., & Davis, R. (2013). Effects of load on the time course of attentional engagement, disengagement, and orienting in reading. *The Quarterly Journal of Experimental Psychology*, *66*(3), 453-470.

Ghahghaei, S., & Verghese, P. (2015). Efficient saccade planning requires time and clear choices. *Vision research*, *113*, 125-136.

Ghahghaei, S., & Walker, L. (2016). The crowding factor method applied to parafoveal vision. *Journal of Vision*, *16*(11), 30-30.

Gersch, T., Kowler, E., & Dosher, B. (2004). Dynamic allocation of visual attention during the execution of sequences of saccades. *Vision Research*, *44*(12), 1469-1483.

Gersch, T., Kowler, E., Schnitzer, B., & Dosher, B. (2008). Attention during sequences of saccades along marked and memorized paths. *Vision Research*, *49*(10), 1256-1266.

Grainger, J., Dufau, S., & Ziegler, J. C. (2016). A vision of reading. *Trends in Cognitive Sciences*, *20*(3), 171-179.

Häikiö, T., Bertram, R., Hyönä, J., & Niemi, P. (2009). Development of the letter identity span in reading: Evidence from the eye movement moving window paradigm. *Journal of Experimental Child Psychology*, *102*, 167-181.

Hoffman, J., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception & Psychophysics*, *57*(6), 787-795.

Inhoff, A.W., Pollatsek, A., Posner, M.I., Rayner, K. (1989). Covert attention and eye movements during reading. *Quarterly Journal of Experimental Psychology A: Human Experimental Psychology*, *41*, 63–89.

Inhoff, A.W., Starr, M., & Shindler, K.L. (2000). Is the processing of words during eye fixations in reading strictly serial? *Perception & Psychophysics*, *62*, 1474-1484.

Itti, L., Rees, G., & Tsotsos, J. (2005). Models of bottom-up attention and saliency. *Neurobiology of attention*, *582*.

Kowler, E. ,Anderson, E. ,Dosher, B. & Blaser, E. (1995). The role of attention in the programming of saccades. *Vision Research*, *35*(13), 1897-1916.

Kowler, E., & Blaser, E. (1995). The accuracy and precision of saccades to small and large targets. *Vision Research*, *35*(12), 1741-1754.

LaBerge, D. & Brown, V. (1989). Theory of attentional operations in shape identification. *Psychological Review*, *96 (1)*, 101-124.

Laubrock, J., Kliegl R, Engbert R. (2006). SWIFT explorations of age differences in eye movements during reading. *Neuroscience& Biobehavioral Review*, *30*(6):872-84.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human, Perception & Performance*, *21*(3), 451- 468.

Lavie, N. & Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Perception & Psychophysics*, *56* (2), 183-197.

Legge, G. E., Cheung, S. H., Yu, D., Chung, S. T., Lee, H. W., & Owens, D. P. (2007). The case for the visual span as a sensory bottleneck in reading. *Journal of Vision*, *7*(2), 9-9.

Linnell, J. K., & Caparos, S. (2011). Perceptual and cognitive load interact to control the spatial focus of attention. *Journal of Experimental Psychology: Human, Perception & Performance*, 37(5), 1643-1648.

Madrid, G. J., Lavie, N., & Lavidora, M. (2011). Asymmetrical perceptual load in lateralised word processing. *European Journal of Cognitive Psychology*, *22*(7), 1066- 1077.

McConkie, G. W., Kerr, P. W., & Dyre, B. P. (1994). What are 'normal' eye movements during reading: toward a mathematical description. In J. Ygge & X. Lennestrand (Eds.), *Eye movements in reading* (pp. 315–327). Elsevier: Oxford.

Miellet, S., O'Donnell, P., & Sereno, S. (2009). Parafoveal magnification: visual acuity does not modulate the perceptual span in reading. *Psychological Science*, *20* (6), 721- 728.

Montani, V., Facoetti, A., & Zorzi, M. (2014). Spatial attention in written word perception. *Frontiers in human neuroscience*, *8*.

Motter, B., & Simoni, D. (2008). Changes in the functional visual field during search with and without eye movements. *Vision Research*, *48*(22), 2382–2393.

Najemnik, J., & Geisler, W. S. (2005). Optimal eye movement strategies in visual search. *Nature*, *434*(7031), 387-391.

Nuthmann, A., & Engbert, R. (2009). Mindless reading revisited: An analysis based on the SWIFT model of eye-movement control. *Vision Research*, *49*, 322-336.

Parks, N. A., Hilimire, M. R., Corballis, P. M. (2011). Steady-state signatures of visual perceptual load, multimodal distractor filtering, and neural competition. *Journal of Cognitive Neuroscience*, *23*(5), 1113-1124.

Pollatsek, A., Bolozky, S., Well, A. D., & Rayner, K. (1981). Asymmetries in the perceptual span for Israeli readers. *Brain and Language*, *14*(1), 174-180.

Pollatsek, A., & Rayner, K. (1992). What is integrated across fixations? In K. Rayner (Ed.), *Eye movements and visual cognition: Scene perception and reading*. New York, NY: Springer-Verlag.

Posner, M. I., Snyder, C. R. R., & Davidson B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: Genera*l, *109 (2*), 160-174.

Rayner, K. (1975a). The perceptual span and peripheral cues in reading. *Cognitive Psychology*, 7, 65-81.

Rayner, K. (1975b). Parafoveal identification during a fixation in reading. *Acta Psychologica*, 39, 271-282.

Rayner, K., & Clifton, C. J. (2009). Language processing in reading and speech perception is fast and incremental: implications for event-related potential research. *Biological Psychology*, *80*(1), 4-9.

Rayner, K., Liversedge, S. P., & White, S. J. (2006). Eye movements when reading disappearing text: The importance of the word to the right of fixation. *Vision Research, 46*, 310–323.

Rayner, K., Murphy, L., Henderson, J., M, & Pollatsek, A. (1989). Selective attentional dyslexia. *Cognitive Neuropsychology*, *6*, 357-378.

Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review*, *105*, 125–157.

Reichle, E. D., Rayner, K. & Pollatsek, A. (2003). The E-Z reader model of eye- movement control in reading: comparisons to other models. *Behavioral & Brain Sciences*, *26*, 445–526.

Reilly, R., & O'Regan, J. K. (1998). Eye movement control in reading: A simulation of some word-targeting strategies. *Vision Research*, *38*(2), 303-317.

Reingold, E. M., Reichle, E. D., Glaholt, M. G., & Sheridan, H. (2012). Direct lexical control of eye movements in reading: Evidence from a survival analysis of fixation durations. *Cognitive Psychology*, *65*, 177–206.

Renninger, L. W., Verghese, P., & Coughlan, J. (2007). Where to look next? Eye movements reduce local uncertainty. *Journal of Vision*, *7*(3), 6-6.

Richter, E. M., Engbert, R. Kliegl, R. (2006). Current advances in SWIFT. *Cognitive Systems Research*, *7* (1), 23-33.

Sperling, G., & Melchner, M. J. (1978). The attention operating characteristic: Some examples from visual search. *Science*, *202*, 315-318.

Sutherland, N. S. (1959). Stimulus analysing mechanisms. Mechanisation of Thought Processes: National Physical Laboratory Symposium No. 10, Vol. II, 575-609.

Treisman, A. M. (1969). Strategies and models of selective attention. *Psychological review*, *76*(3), 282.

Visser, T. A., Boden, C., & Giaschi, D. E. (2004). Children with dyslexia: evidence for visual attention deficits in perception of rapid sequences of objects. *Vision Research*, *44*(21), 2521-2535.

Waechter, S., Besner, D.,& Stolz, J. A. (2011). Basic process in reading: Spatial attention as a necessary preliminary to orthographic and semantic processing. *Visual Cognition*, *19*(2), 171-202.

Walker, R., Deubel, H., Schneider, W.X. & Findlay, J.M. (1997). The effect of remote distractors on saccade programming: evidence for an extended fixation zone. *Journal of Neurophysiology*, *78*, 1108-1119.