The dynamics of attention in active reading and effects of load

by

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I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning.

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Ethical approval

All experiments were approved by Goldsmiths, University of London. For those experiments that were run at the Smith-Kettlewell Eye research Institute, we had Institutional Review Board (IRB) approval.

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Abstract

We investigated the dynamics of spatial attention in an active viewing task, namely reading, and the effects of the load of target words on these dynamics. We showed that, over the course of a fixation, attention was modulated by the load of the fixated word and the upcoming word.

The load of words was manipulated by varying word frequency and the orthographic familiarity of the first trigram in words. In a variation of the dynamic-orienting paradigm (Fischer, 1999), participants read sentences or strings of words for the primary task and discriminated gaze-contingent probes - occurring with variable spatial and temporal offsets from the first fixations on words - for the secondary task. Reading was evidenced by longer fixation durations on words with lower frequencies. The accuracy of probe discrimination was used to index attention.

Early in a fixation, attention was focused on the gaze more when the fixated word was lower in frequency. This early effect of frequency was revealed for reading sentences and strings of words provided words were previewed before being fixated.

Attention defocused over time and, by halfway through a fixation, orienting towards the to-be-fixated location (i.e., towards the right) began. Late in a fixation, attention had oriented more to the right of the gaze for high- than low-frequency words. Shortly before the saccade to the upcoming word, and during preview of this word, its processing was sufficiently advanced to affect attention: specifically, less attention remained at the gaze location when the first trigram of the upcoming word was orthographically less familiar.

In sum, we showed that the moment-to-moment processing load of words affects the dynamics of spatial attention.

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Chapter 1

Introduction

1.1 Introduction: attention and reading

Reading English text involves overt attention shifts through horizontal left-to-right eye movements, or saccades, as well as covert shifts of attention while the eyes are fixated on a given word. Covert (spatial) attention is a processing resource that can be temporarily decoupled from the point of fixation to enhance visual processing elsewhere (Helmholtz, 1867/1962) and it always leads the eyes (e.g., Bryden, 1961; Deubel & Schneider, 1996; Fischer, 1999; Gersch, Kowler & Dosher, 2004; Hoffman & Subramaniam, 1995; Kowler & Blaser, 1995).

The term '(covert) attention' in this work refers to spatial visual attention. This is distinct from the standard use of the term in models of eye movement control in reading. In the latter, the term usually refers to lexical attention and the processing of word(s) at lexical levels to extract their meaning. Spatial attention is suggested to be a necessary stage in the processing of word(s) to lexical levels (Waechter, Besner & Stolz, 2011).

Given that attention is necessary for word recognition (Waetcher et al., 2011) and that attention leads the eyes, reading provides a real-world framework within which to investigate the spatio-temporal distribution of attention. Manipulating the processing demand of a word (e.g., via manipulating the word's length, frequency, orthographic familiarity, or predictability) enables the investigator to influence the load on the reader and to examine the way in which this load impacts on the spatiotemporal distribution of attention.

Morrison (1984) proposed that, in normal reading, over the course of a fixation, attention is first centred on the fixated word in order to process the word and then shifts towards the next word in order to select the next location for the eyes. However, the proposed engagement and orienting of attention and their timecourse were not explicitly stated. To date, the distribution of attention over the course of a fixation in reading is not clear. Studies on reading have not explicitly addressed (i) how attention accompanies eye movements or (ii) how attention is distributed over the course of a fixation or (iii) whether attention is affected by those aspects of the word/text/task that affect the eyes.

Studying attention in reading is important given that deficits in the focusing and/or orienting of attention are reported in dyslexics (e.g., Geiger, Lettvin, & Zegarra-Moran, 1992; Dhar, Been, Minderaa, & Althaus, 2008; for a recent review, see Bellocchi, Muneaux, Bastien-Toniazzo & Ducrot, 2013). However, the contribution of these deficits to impaired reading behaviour (e.g., longer fixation durations and shorter saccades; Ashby, Rayner & Clifton, 2005; Rayner, 1998) is not clear.

Studying eye-movement behaviours, such as fixation durations and the metrics of saccades, in reading can inform us about attention, given that attention (i) is necessary for word recognition (Waechter et al., 2011) and (ii) leads the eyes (e.g., Bryden, 1961; Deubel & Schneider, 1996; Fischer, 1999; Gersch et al., 2004; Hoffman & Subramaniam, 1995; Kowler & Blaser, 1995). For example, the eyes remain longer on words with lower frequency (e.g., Rayner, 1998; Reingold, Yang & Rayner, 2010; Sereno, 1992; Staub, White, Drieghe, Hollway & Rayner, 2010). Furthermore, the eyes land closer to the beginning of a word when its first trigram is orthographically more demanding (e.g., Vonk, Radach, & van Rijn, 2000; White & Liversedge, 2004a, 2004b, 2006). One would expect that manipulation of the frequency of the words and the orthographic familiarity of the first trigrams in the words should affect attention at some time points over the course of a fixation. However, the eyes are still over the course of a fixation and do not inform us about the dynamics of attention. Acquiring a better understanding of the dynamics of attention in normal readers will help us (i) better understand the flow of information processing in reading and (ii) whether attentional deficits (e.g., deficits in focusing or orienting attention) directly affect this flow and/or the programming of the upcoming saccade.

In the work reported here, we investigated the dynamics of attention over the course of a fixation, in normal reading, and the effects of load on these dynamics. We did so by using a variation of the dynamic-orienting paradigm (Fischer, 1999) where, on each trial, the participant read a line of text, for the primary task. For the secondary task, the participant discriminated the orientation of a gaze-contingent probe that occurred with a variable spatial and temporal offset from the first fixation on a target word. The processing load of the target word was manipulated by manipulating its frequency and the orthographic familiarity of its first trigram. Reading was evidenced by longer fixation durations on words with lower frequencies (Rayner & Raney, 1996).

Following Morrison (1984), we proposed two phases for attention, over the course of a fixation: the engagement phase, during which attention is engaged with the processing of the fixated word, and the orienting phase, during which attention orients away from the fixated word and towards the upcoming word and engages with the processing of the upcoming word. We proposed that, during the engagement phase (i.e., the first half of a fixation), attention would be focused on the gaze location more for low- than high-frequency words. This is because, in active reading[1], processing of a word starts while the eyes are still on the preceding word; that is, the word is previewed before being fixated (Rayner 1975a, 1975b). Given preview, we expected that processing of the word, early during the first fixation on it, should be sufficiently advanced to reach those levels that correspond to the word's frequency. Consequently, we expected that attention would be more focused around the gaze location for low- than high-frequency words.

During the orienting phase (i.e., the second part of a fixation), we proposed that attention would orient towards the next saccadic target earlier when the fixated word is higher in frequency, given that (i) the eyes leave a high-frequency word earlier than a low-frequency one (e.g., Rayner, 2009) and (ii) that attention leads the eyes. Before the eyes leave the fixated word, the upcoming word is being covertly previewed and its processing has started; in other words, attention is engaged with the processing of the upcoming word. Therefore, we proposed that attention would be affected by the processing of the upcoming word just before the saccade to the upcoming word: specifically, we proposed that less attention would remain at the gaze location when the processing of the upcoming word is more demanding, for example, when the first trigram in the upcoming word is orthographically less familiar.

The work provided here brings together work on attention and load, eye movements and reading. In section 1.2, we review (i) studies on eye movements and the

[1] The term 'active reading' is used to clarify that reading involves eye movements as opposed to 'static reading' when the eyes are static, for example, reading under a rapid serial visual presentation (RSVP) paradigm.

effects of load on the eyes and (ii) studies that looked at the effects of manipulating the availability of the visual information from the fixated word and/or the upcoming words on eye movements in reading using gaze-contingent display change paradigms. Although studies that are reviewed in section 1.2 do not directly look at attention, the results of these studies can shed more light on our understanding of the dynamics of attention given that attention (i) is necessary for word recognition and leads the eyes (e.g., Bryden, 1961; Deubel & Schneider, 1996; Fischer, 1999; Gersch, Kowler & Dosher, 2004; Hoffman & Subramaniam, 1995; Kowler & Blaser, 1995). Thus, we can acquire more information on attention by studying the effects of the manipulation of visual information from the text on eye movements. Section 1.3 reviews relevant studies that directly measured attention using word-based stimulus. In this section, we review studies that looked (i) at the effects of the load of a target word on the focus of attention on the word, in static viewing conditions, and (ii) the effects of the load of a target word on attention, in a task that required a single saccade to the word. Then, we review in details Fischer's (1999) study in which attention and the effects of load in a reading task were investigated, using a dynamic-orienting paradigm. Fischer's (1999) paradigm was designed to measure attention directly by using a secondary task in which participants detected gaze-contingent probes. The primary task was reading. The reaction time to detect the probe was the measure of attention.

We used a variation of the dynamic-orienting paradigm (Fischer, 1999) in which we increased the sensitivity of the probe by requiring participants to discriminate the orientation of the probe rather than simply detecting it. Section 1.4 details our assumptions and predictions in terms of the dynamics of attention, over the course of a fixation, in reading.

1.2 What the eyes tell us about attention

Given that attention leads the eyes (e.g., Bryden, 1961; Deubel & Schneider, 1996; Fischer, 1999; Gersch, Kowler & Dosher, 2004; Hoffman & Subramaniam, 1995; Kowler & Blaser, 1995), studying eye movements and the effects of load on them can inform us about attention, especially for the orienting phase. In section 1.2.1, we first clarify what we mean by load throughout the thesis. Then, in section 1.2.2, the effects of load on eye movements in reading are briefly reviewed. Section 1.2.3 covers display-change paradigms that are designed to study how the availability of visual information from the text around the gaze location affects eye movements in reading. We propose that only if visual information from words is attended can it affect saccade programming. Thus, we can acquire more information on attention by studying the effects of manipulating of visual information on eye movements.

1.2.1 What is load?

Before we look at the effects of load, we need to clarify what we mean by it. The term 'load' may refer to different things and has different meanings depending on the field of study and the context. For example, in the attention literature, load can refer to the perceptual load of a stimulus, that is, how much a stimulus engages the attentional resources in order to be processed.

In the reading literature, the load of a word refers to how hard it is to access the word's meaning; for example, the word 'trench' is less frequent than the word 'church' and, thus, it is harder to access the meaning of 'trench' than 'church'. Morton (1969) suggested that low-frequency words demand more attentional resources for encoding information than high-frequency words; that is, words with lower frequencies have a higher load.

In addition to the load of a word, the load of a reading task affects how much attentional resources are needed to process the word. Different reading instructions (e.g. scanning versus proofreading a text) impose different levels of demand for attention for the participant. In addition, the load of the reading task is different for young versus old, beginners versus skilled, or normal versus dyslexic readers. Thus, both the load of the words and the load of the reading task affect how demanding reading a word is. We note that, what all these meanings of the term 'load' have in common is the 'demand for attention'. In this thesis, by a higher 'load' we mean more demand for attention.

A common paradigm used to measure the load of an *isolated* word is the word-recognition task (New, Ferrand, Pallier & Brysbaert, 2006). In this task, participants make a speeded manual response to indicate whether a string of letters is a word or a non-word. Manual responses are slower for more demanding (i.e., higher load) words in the word-recognition task. Manual responses are affected by word length: long words (longer than 8 characters in length) are processed slower, resulting in longer reaction times, than words with an average length (e.g., between 5 and 8 characters in length), suggesting that the length of the word increases its processing load (New, Ferrand, Pallier, 2006). Furthermore, a difference of one logarithm in the printed frequency of words leads to a difference of about 50 ms in reaction times in word recognition tasks (Scarborough, Cortese & Scarborough, 1977). This is in line with Morton's (1969) suggestion that low-frequency words demand more attention for encoding information than high-frequency words.

In addition to a word's frequency and length, the orthographic familiarity of its letters affects its load. Frequent letter sequences may look visually more familiar than infrequent letter sequences (Findlay & Walker, 1999). A 'more familiar' perception of a letter sequence could mean a higher 'signal to noise ratio' for those activations in the brain that represent the sequence and, therefore, less demand for attentional resources. In the work provided here, we controlled the lengths of the words and manipulated word frequency and the orthographic familiarity of the first three letters (i.e., the first trigram) in words. We explain in sections 1.2.3.1 and 1.2.3.2 why we controlled the orthographic familiarity of the first three letters as opposed to, for example, the first two or four letters.

1.2.2 Eye movements and load effects in reading

Similar to reaction times in word-recognition tasks, fixation durations are affected by the length and frequency of the fixated word. The eyes fixate for longer on longer words (e.g., Kaakinen & Hyönä, 2010) or less frequent words (e.g., Rayner, 1998; Reingold et al., 2010; Sereno, 1992; Staub et al., 2010).

For different types of load, the timecourse of the effect of load on reading times is not the same. Some load manipulations affect early measures of eye movement such as the duration of the very first fixation on a word. Others affect later measures such as the gaze duration (i.e., the sum of all fixations on a word before the eyes leave it). For example, word frequency affects both first fixation durations and gaze durations whereas word length only affects gaze durations (e.g., Pollatsek, Juhasz, & Reichle, 2008). This shows that the processing of a word at those levels that correspond to its frequency occurs sufficiently early to affect the duration of the first fixation on the word.

Not only a word's lengths or frequency, but also its rank in the line of text (i.e., how many words it is preceded by) affects how long the eyes fixate on it. Fixation durations increase with an increase in the rank of the word in the line of text (Kuperman, Dambacher, Nuthmann, & Kliegl, 2010). Using non-word stimulus, Williams and Pollatsek (2007) showed that, in a reading-like search task that required finding a target letter 'O' embedded in clusters of landolt 'C's, fixation durations on clusters increased with an increase in the rank of the clusters. Thus, in reading-like tasks, fixation durations increase with an increase in the rank of the stimulus that is fixated, even in the absence of higher lexical levels or the context of a sentence.

When there is a context, for example, in reading sentences, integrating the word's meaning into the context gets harder as the rank of a word in a line of text increases. In addition, the context affects how predictable a word is and the predictability of a word affects its processing load. In fact, the eyes fixate shorter on words that are predictable, as opposed to unpredictable, from their context (Ehrlich & Rayner, 1981; Frisson, Rayner & Pickering, 2005; Rayner, Reichle, Strouds & Williams, 2006). In the work presented here, we manipulated frequency of target words and the orthographic familiarity of the first three letters in them. The predictability of these words was controlled to be low. In other words, these target words were not predictable.

In addition to context, the instruction/aim of the reading task affects the eyes. If the reading task is very demanding (e.g., reading for proofreading as opposed to reading for comprehension), participants fixate on words for longer (Kaakinen & Hyönä, 2010). Also, the same reading task is more demanding for dyslexics than normal readers, resulting in slower reading (e.g., Rayner, Murphy, Henderson & Pollatsek, 1989).

Given that attention leads the eyes and the eyes leave a low-frequency word later than a high-frequency word, it is obvious that the orienting of attention towards the next word should be delayed for fixated words with lower frequencies. Furtheremore, given that attention is necessary for word recognition (Waechter et al., 2011) one would expect that when the fixated word has a higher load, for example, when it is lower in frequency, more attention should be engaged with the word. However, the dynamics of engagement and orienting and the effects of load are not clear.

Studying eye movements in normal reading (i.e., when there is no gaze-contingent display-change) gives us some insight to the effects of load on the engagement and orienting phases of attention. More information on the dynamics of attention comes from studies in which visual information from the text around the gaze location is manipulated. These studies are priminarily designed to investigate the effects of these display-changes on eye movements. Nevertheless, how the eyes move when there is a display-change, as opposed to when there is not, can give us more insight into the dynamics of attention.

1.2.3 Evidence from display-change paradigms

In section 1.2.3, we briefly review the paradigms that can be used to infer some aspects of the dynamics of attention, over the course of a fixation, in reading. These paradigms are designed to look at effects of the availability of visual information at and/or around the gaze location on eye movements, in reading, by using gaze-contingent display changes. The *moving-window* paradigm (section 1.2.3.1) and the *boundary* paradigm (section 1.2.3.2) are used to look at the effects of the validity of visual information from a window around the gaze location on eye movements. In these two paradigms, display changes occur during *saccades*. Thus, the effects of change are integrated over the course of a fixation and, therefore, one might infer some characteristics of attention over *space*, but not time, from the results of these paradigms. The results of the moving-window paradigm show that the distribution of attention is skewed to the right (i.e., the default direction of the next saccade in reading English texts) and is skewed more when the reading task is less demanding. The results of the boundary-paradigm show that on the right of the gaze location attention is more when the fixated word is more frequent. The *disappearing-text* paradigm (section 1.2.3.3) and *switching-text* paradigm (section 1.2.3.4) are used to look at how a change in visual information from the fixated word, during the course of a *fixation*, affects eye movements. Therefore, one might infer some characteristics of attention over *time* from the results of these two paradigms. The results of the disappearing-text paradigm show that during the first 60 ms or so of a fixation, visual information of the fixated word is necessary for fluent reading; thus we infer that attention is engaged with the processing of the fixated word at least during this time window. The results of the switching-text paradigm show that visual information of the fixated word is less likely to be processed

120 ms into a fixation than 50 ms into a fixation; thus, we infer that the orienting phase of attention has already started by 120 ms into a fixation.

1.2.3.1 The moving-window paradigm and the perceptual span

Because of a sharp drop in acuity with an increase in the distance from the fovea (Virsu & Rovamo, 1979; Rovamo & Virsu, 1979), we can only extract information within a limited window around the gaze. Besides, the strength of information that is extracted depends on attention (e.g., Carrasco, Ling, & Read, 2004). Consequently, readers do not obtain useful information from those parts of the text that (i) are very far from their gaze location or (ii) receive no attention. For a reading task, this means that only the information within a limited span around the gaze location can affect reading, and therefore, how the eyes move.

Studies on the size of the attentional span in reading go back to about a century ago (e.g., Huey, 1908; Woodworth, 1938). In 1975, McConkie and Rayner developed a moving-window technique in which they showed that visual information from a limited window around the gaze location affects the eyes in reading. Thus, letters within a limited window around the gaze location receive sufficient attention, during engagement and/or the orienting phases, to affect reading and/or the programming of the saccades.

Specifically, the text in McConkie and Rayner's (1975) study was exposed only inside a gaze-contingent window around the gaze and was masked elsewhere. As the eyes moved through the text, the window moved with the eyes during saccades (Figure 1.1). Changes in stimuli that occur during a saccade are unlikely to be noticed because of saccadic suppression (Erdmann & Dodge, 1898; Haber & Hershenson, 1973).

McConkie and Rayner (1975) showed that, for big windows, the speed of reading was not different from that for normal reading. As the size of the window decreased, reading became more difficult and the speed of reading became slower. For a window that was extended on the left side of the gaze to the beginning of the fixated word (but no more that 3 or 4 characters to the left of the gaze) and about 12-14 characters rightwards of the gaze location, the speed of reading did not change compared to when there was no manipulation of the stimuli (also see McConkie & Rayner, 1976; Rayner, 1986; Rayner, Well & Pollatsek, 1980; Rayner, Well, Pollatsek & Bertera, 1982). This critical window around the gaze is called the *perceptual span*.

The perceptual span is, therefore, a span around the gaze from which useful information can be extracted. It is skewed in the direction of reading: it is skewed to the right for readers of western texts and to left for readers of texts that are written form right to left (Pollatsek, Bolozky, Well & Rayner; 1981).

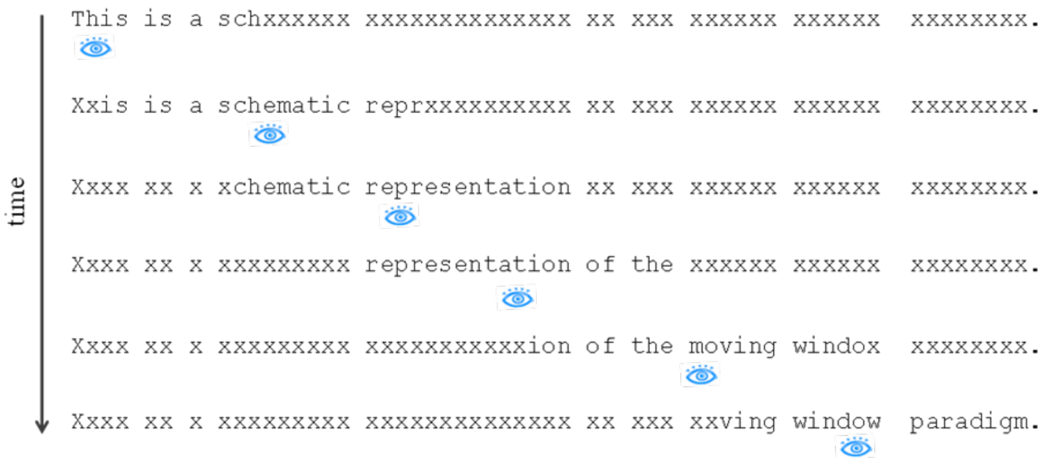

Figure 1.1. The moving-window paradigm. An example of the moving window paradigm (Rayner, 1975) where letters within a window that extends 10 characters to the left and 10 characters to the right of the gaze location are exposed. In this example, letters outside the window are masked by ‘X’s but word boundaries, ‘blank spaces’, are preserved. As the eyes move through the text, the window moves with the eyes during saccades.
: gaze location.

Although the perceptual span extends about 14 characters rightwards of the gaze location, in reading English texts, the window within which the identity of letters can be extracted is much smaller, about 8 characters rightwards of the gaze location. The window from which a letter’s features can be extracted (e.g., the letter ’h’ and the letter ‘b’ share similar features but are not identical) is about 11 characters rightwards of the gaze location (Häikiö, Bertram, Hyönä & Niemi, 2009). Beyond that, up to about 14 to 15 characters, only low spatial frequency information, such as word boundaries, can be extracted (Rayner et al., 1982; Underwood & McConkie, 1985). Note that this is not simply because of a drop in acuity given the asymmetry in the span on the left and the right side of the gaze location. Thus, the type of information that can be extracted from letters within the span depends on their location.

The size of the perceptual span, in characters, does not change when the letter size, in visual degrees, changes (Pollatsek, & Rayner, 1992), suggesting that the span is not restricted by visual acuity and that it is an attentional rather than visual span. Furthermore, a study by Miellet, O'Donnell, and Sereno (2009) showed that attention and ongoing processing, but not visual acuity, determine the size of the perceptual span. Miellet et al. (2009) introduced a new variation of the moving-window paradigm where they used gaze-contingent *parafoveal magnification*. Specifically, parafoveal magnification was performed for all letters in the line of text upon saccades. Therefore, visual acuity was no longer a bottleneck limiting information processing in the parafoveal region. Miellet et al. (2009) replicated the same window size for the right side of the perceptual span as was found without parafoveal magnification; that is, 14 characters.

The greatest support for the perceptual span being an attentional span comes from studies that looked at the effect of the load of the reading task on the perceptual span. The size of the span depends on the difficulty of the reading task, the span is narrower when the reading task is more demanding. For example, proofreading a text is more demanding than reading it for comprehension resulting a smaller span for the former (Häikiö et al., 2009; Inhoff, Pollatsek, Posner, & Rayner, 1989).

In terms of word units, the perceptual span extends roughly to cover the fixated word and the two words that follow it. Rayner et al. (1982) showed that when the window contained the fixated word and the upcoming word (i.e., the word to the right of the fixated word in western texts) the speed of reading was almost equal to the normal speed of reading. On the other hand, when the window included only the fixated word the speed of reading dropped to 60 %. Interestingly, when the fixated word and only the first three letters in the upcoming word were exposed the speed of reading was almost as fast as the normal speed of reading. The authors concluded that the processing of at least the first three letters in the next word can occur while the eyes are still on the currently fixated word.

In sum, the perceptual span is an attentional span given that (i) it is affected by the load of the task, (ii) it is skewed in the direction of reading and (iii) its extent is measured in character rather than visual degree units. The moving-window paradigm was a break through method to study what parts of the text are processed, over the course of a fixation. The findings on perceptual span suggest that attention is asymmetric around the gaze location at least at some points during a fixation. Given that attention leads the eyes, an obvious conclusion is that, at least during the orienting phase, attention should be more on the right than left of the gaze location. However, it is also possible that there is more attention on the right than the left side of the gaze also during the engagement phase of attention. In addition, given that denying a valid visual information from the first three letters in the upcoming word significantly reduced the speed of reading, one might expect that at least the first three letters in the upcoming word are attended at least at some points during the current fixation; an obvious conclusion would be that the letters in the upcoming word are attended during the orienting phase of attention before the saccade to the upcoming word.

The method, however, reveals nothing about the dynamics of attention. This is because display changes occur upon saccades and any changes in attention are integrated over the course of a fixation. Thus, the perceptual span is an average of all the locations that are attended, at various points in time, over the course of a fixation. Furthermore, whereas the measure that is used in this paradigm (i.e., the speed of reading) is sensitive to the manipulation of the load of the reading task, it is not very sensitive to the manipulation of the load of target words in the text. This is because the speed of reading is not a sufficiently early measure to reveal effects of the load of a given word on the span at the point when the word is fixated. Thus, the dynamics of attention during the engagement and orienting phases and effects of word load on these dynamics are not clear.

In a follow-up study, Rayner (1975a, 1975b) implemented a new paradigm called the *boundary paradigm* (presented in section 1.2.3.2). In this paradigm, effects of the load of the fixated word, and/or the next word, on the eyes was are investigated using an earlier behavioural measure, that is, the duration of fixations on words rather than the speed of reading. The results of the studies using the boundary paradigm give us some insight to the effects of load of the fixated word on attention.

1.2.3.2 The boundary paradigm and preview

In the boundary paradigm, visual information of the to-be-fixated word (e.g., book) is manipulated. The letters in the to-be-fixated word are either identical to the letters in the word (i.e. book; valid preview) or not (e.g., raqb; invalid preview). If not, upon the saccade to the word, when the eyes cross the word's boundary for the first time, the letters change into the letter in the word (i.e., 'raqb' changes to 'book') during the saccade. Having a valid preview is shown to decrease reading times on the word after it is fixated (the preview benefit) given that information that is obtained during previewing is integrated across the saccade to the word (e.g., Inhoff et al., 2000; Rayner & Clifton, 2009). The results of studies that implemented the boundary paradigm in reading show that the processing load of the fixated word affects the preview of the upcoming word. Preview of the word in turn affects how long the eyes fixate on it (Rayner, 1975a, 1975b) and where the eyes land on it (e.g., Hyönä, 1995). Given that preview affects where the eyes land on the word and that attention leads the eyes, an obvious conclusion is that preview of the upcoming word affects attention at least during the orienting phase of attention.

Here, we first provide an example of the boundary paradigm in a task that requires a single saccade to an isolated word (section 1.2.3.2.1). Then, we look at studies that implemented the boundary paradigm in active reading (section 1.2.3.2.2). This is followed by a section on how preview affects the programming of the upcoming saccade (section 1.2.3.2.3).

1.2.3.2.1 Preview in a single saccade to a target word

To clarify the idea of the boundary paradigm, we refer to a study by Rayner, McConkie and Zola (1980) where the boundary paradigm was implemented in a task that required a single saccade to an isolated target word. This study showed that participants benefited from having a 'preview' of the initial letters of the target word, before making a saccade to the word.

Specifically, the participant fixated on a central fixation point. Then a string of letters was presented in the parafovea. The participant made a saccade to the string. Upon the saccade, the string changed into a word (i.e., the word was exposed). The participant's task was to name (pronounce aloud) the word. In some trials, the beginning letters in the string were the same as the beginning letters in the to-be-exposed word, that is, participants received a valid 'preview' of the beginning letters of the word before fixating it. In other trials, the beginning letters in the string and the to-be-exposed word were not the same, that is, participants did not receive valid preview of the beginning letters of the word before fixating it.

When the preview of the beginning letters was valid, compared to when it was not, correct naming was speeded as indexed by shorter naming onset times. Thus, parafoveal information about the beginning letters in the word was extracted during its preview and was used for naming the word. In other words, participants received some 'benefit' from having a 'valid preview' of the beginning letters in the word in the parafovea resulting in speeded naming.

1.2.3.2.2 Preview in active reading

In active reading, the boundary paradigm was first implemented by Rayner (1975a, 1975b). Specifically, Rayner had a target word in each line of the text. Participants were first presented with a string at the location of target word that was either identical to the word or not. Upon the saccade to this string, when the eyes passed an invisible boundary to the left of the string, the string changed into the target word (Figure 1.2). Note that the string remained unchanged if it was identical to the target word in the first place.

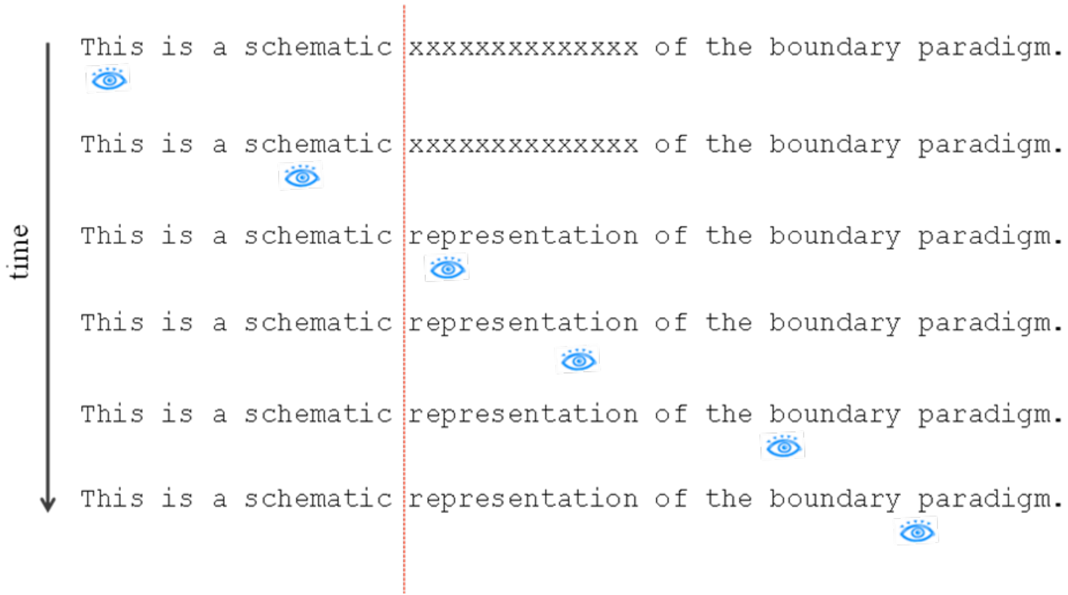

Figure 1.2. The boundary paradigm. An example of the boundary paradigm (Rayner, 1975a). The target word 'representation' was replaced by another string, here 'X's which is not identical to the word itself. When the eyes passed an invisible boundary to the left of the location of the string (here shown by the red line, only for the illustration purpose), the string changed into the target word. In this example, the preview of the target word was invalid.  : gaze location.

Rayner looked at the difference in the duration of first fixation on target words between the two conditions where the previewed string was identical (valid preview) to the word or not (an invalid preview). The author used this difference as a measure of how much information was obtained from the target word before it was fixated. Rayner showed that first fixation durations on target words were on average 40 ms to 80 ms shorter when preview was valid than invalid. In other words, the preview benefit ranged from about 40 ms to about 80 ms.

Participants obtained some preview benefit even when the word was only partially presented before being fixated. For example, if only the first two or three letters of the word was presented and other letters were masked (e.g., Balota & Rayner, 1983; Johnson, Perea & Rayner, 2007; Lima, 1993; Lima & Inhoff, 1985; White, Johnson, Liversedge & Rayner, 2008). However, only little preview benefit was obtained when preview was valid for the last, but not the beginning, letters of a word (Pollatsek & Rayner, 1992). Thus, valid preview of the first two or three letters in the word was crucial for fluent reading.

This is in line with the results of Rayner et al.'s (1982) study that in a moving-window paradigm, when the letters in the fixated word and the first three letters in the upcoming word were preserved, the speed of reading was almost unaffected by the display change (section 1.2.3.1). Using the boundary paradigm, it is shown that the information that is obtained from these letters during the preview (e.g., information about abstract letter codes or orthographic properties or phonological information) is integrated across the saccade to the upcoming word and is used in further processing of the word (e.g., Inhoff et al., 2000; Rayner & Clifton, 2009). Hence, the boundary paradigm, unlike the moving-window paradigm, can help us understand which properties of the upcoming word, or its beginning letter sequences in the upcoming word, are processed during preview and thus attended.

In addition, unlike the moving window paradigm, the boundary paradigm can help us to investigate whether the processing load of the fixated word affects the preview of the upcoming word, and thus, the allocation of attention to the upcoming word. This is because the boundary paradigm uses an earlier behavioural measure (i.e., fixation duration) that is more sensitive to the effects of the load of the fixated word. Using a boundary paradigm, Henderson and Ferreira (1990) showed that the frequency of the fixated word affects the preview benefit from the upcoming word.

Specifically, in Henderson and Ferreira's (1990) study, the participant read single sentences for comprehension where the preview of a target word (i.e., Wn+1) in each sentence was manipulated to be fully available (valid) or not available (invalid) (Figure 1.3). The authors manipulated the processing load of the words that preceded these targets word (i.e., Wn). First, they manipulated the frequency of Wn to be either high or low. Second, they manipulated how syntactically easy/difficult processing of Wn was. So, in the latter case, they used the same word for Wn in both easy and difficult conditions but embedded it into different contexts. They only analysed data for participants who did not notice display change.

Henderson and Ferreira (1990) showed an effect of the manipulation of the load of Wn on how much preview benefit from Wn+1 was obtained for both types of load manipulation: the higher the load of Wn, the smaller the preview benefit for Wn+1. For example, the preview benefit was on average 13 ms smaller when Wn was low rather than high in frequency. The authors reasoned that, in each fixation, the processing load of the fixated word affects the perceptual span so that the span is less extended to the right of the gaze when the fixated word is more demanding.

(a) `Mary bought a chest xxxxxxx the high price.`
`Mary bought a chest despite the high price.`

(b) `Mary bought a truck xxxxxxx the high price.`
`Mary bought a truck despite the high price.`

(c) `She warned that Harry xxxxxx small gifts.`
`She warned that Harry bought small gifts.`

(d) `She warned Harry xxxxxx small gifts.`
`She warned Harry bought small gifts.`

Figure 1.3. Henderson and Ferreira's (1990) study. An example of the stimuli in the Henderson and Ferreira (1990) study. Preview of target words (Wn+1; 'despite' in a and b, 'bought' in c and d) was manipulated to be invalid (1^{st} lines in a, b, c and d) or valid (2^{nd} lines in a, b, c and d) before the eyes fixated them. The load of words that preceded the target words (Wn) was manipulated in two ways: the words were either high ('chest' in a) or low ('truck' in b) in frequency, or they were syntactically easy ('Harry' in c) or difficult ('Harry' in d).

A question that arises here is whether this difference in first fixation durations on Wn+1 was indeed the result of a delay in processing of Wn+1. Alternatively, it could be the result of a ‘spill over’ of processing of Wn even after the eyes fixated on Wn+1. If the difference is the result of a spill over, then the observed preview benefit should be bigger when fixations on Wn are shorter. Such an interaction would suggest that when Wn was more demanding, its processing was not complete before the eyes moved to Wn+1, and this processing continued even when the eyes were on Wn+1, resulting in a perceived bigger preview benefit.

White, Rayner and Liversedge (2005) addressed the above question and replicated the results of Henderson and Ferreira (1990) in a more controlled way and found no interaction. Specifically, they manipulated the frequency of Wn and the validity of preview of Wn+1. Preview of Wn+1, which was a 4-letter word, was either correct (the valid condition) or incorrect (the invalid condition; letters were replaced by random consonants). Only trials where there was a single fixation on Wn followed by a saccade to Wn+1 were analysed.

They found an effect of the frequency of Wn on the preview benefit for Wn+1, for participants who did not notice display changes: when Wn was low in frequency, the preview benefit was on average 56 ms less than when Wn was high in frequency. The authors suggested that the preview benefit was bigger in their study because Wn+1 was shorter compared to Henderson and Ferreira’s (1990). Most importantly, the effects of the load of Wn on preview for Wn+1 was independent of how short or long the fixation on Wn was. Thus, the observed effect of the processing load of Wn on the preview benefit for Wn+1 was not simply a ‘spill over’ effect. Rather, when the eyes were on Wn, the processing of Wn+1 was delayed when Wn was low rather than high in frequency. Thus, both the processing load of the word (e.g., how frequent it is) and the context (e.g., how syntactically easy/difficult it is) affect the perceptual span.

In addition to the word’s processing load, other factors such as whether or not two adjacent words are linguistically unified affect preview. Häikiö, Bertram and Hyönä (2010) showed that in reading Finnish texts, readers obtained more preview for an upcoming word when it was the second part of a compound word (e.g. “ghost story”) than when it was a noun preceded by an adjective (e.g., “vivid story”). They reasoned that the perceptual span is skewed towards the right more when words are both spatially and linguistically unified. Therefore, more preview benefit was obtained for the second part of a compound word than for a word preceded by an adjective.

Using a boundary paradigm, Binder, Pollatsek and Rayner (1999) manipulated the *post-view* of Wn-1 to be either identical or different. When the post-view was identical, Wn-1 remained the same when the eyes landed on Wn. When the post-view was different, on the other hand, Wn-1 changed to another word when the eyes landed on Wn. When the post-view was different, the post-view either fit the meaning of the sentence or did not fit. Binder et al. showed that regressive saccades back to Wn-1 increased when the post-view of Wn-1 was different, as opposed to identical, and even more when the post-view did not fit the meaning of the sentence. Thus, Wn-1 was analysed even when the eyes moved to Wn.

In a study by Inhoff, Eiter and Radach (2005), preview of target words was manipulated not during the saccade to the words but during the first fixation on the words that preceded them. In this study, the text was entirely written in alternating case. The target word was masked with a visuo-spatially and linguistically non-distinct pseudo-word after some temporal offset (0 ms, 70 ms, 140 ms or 210 ms) from the beginning of the first fixation on the word that preceded the target word. Letter case in the word that preceded the target word altered simultaneously with the preview change in the target word to prevent the reader from being distracted by the visual change in the parafoveal region. Preview benefit on the first fixation on target word was the measure of how much the target word was processed when the eyes were on the preceding word. The authors showed that when the preview of the target word was valid only during the first 70 ms of the first fixation on the preceding word, participants did not benefit from this preview. When preview was valid after 140 ms, participants received the most benefit. Interestingly, participants received some preview benefit when preview was valid between 70 ms and 140 ms into a fixation. This suggests that the orienting of attention to the target word from the preceding word occurred between 70 ms and 140 ms into a fixation.

In sum, the results of the studies that used the boundary paradigm suggest that the perceptual span is variable and is affected by a word's processing load; the perceptual span in turn affects the amount of information that is obtained from the upcoming word during preview. The perceptual span may occasionally cover the previous word. Nevertheless, more attention is allocated to the upcoming, as opposed to the previous word. Over all, less attention is allocated to the upcoming word when the fixated word is more demanding. The information that is obtained during preview from the *upcoming word* affects where the eyes land on the upcoming word (e.g., Hyönä, 1995). Given that attention leads the eyes, one might conclude that preview of the upcoming word affects attention at least during the orienting phase. In section 1.2.3.2.3, the effects of preview on the eyes, in reading, are briefly reviewed.

1.2.3.2.3 The effects of preview on where the eyes land next

In reading, the intended landing position of the saccade to the upcoming word is generally assumed to be the centre of the word (O'Regan & L'evy-Schoen, 1987). However, the behavioral data show that the eyes usually undershoot this location and land on somewhere between the beginning and the centre of the word (Rayner, 1979). The distribution of landing positions on a word depends on the distance between the beginning letter of the word and the previous gaze location which is called the *launch site* (see Figure 1.4 a,b). The farther away the launch site from the word, the closer the eyes land to the beginning of the word (Underwood, 1998).

Landing positions are also affected by the processing load of the beginning letters in words. For example, Hyönä (1995) showed that when the first letters of the upcoming word were irregular, they influenced the landing position of the saccade to the word and moved it towards the beginning of the upcoming word (Figure 1.4 c,d). Radach, Inhoff and Heller (2004) showed that when the first quadrigrams (i.e., the first four letters) in a word were orthographically less familiar, landing position shifted towards the beginning of words. In line with this, Vonk et al. (2000) manipulated the frequency (token) of the initial trigrams (i.e., the first three letters) in target words and again found that landing positions on the words were shifted towards the beginning of them when the initial trigrams were less frequent (i.e., were less orthographically familiar) for a wide range of launch sites (Plummer & Rayner, 2012; White & Liversedge, 2004a, 2004b, 2006). Furthermore, the authors showed that the distribution of launch sites was not affected by the experimental manipulation, indicating that the manipulation did not change the probability of refixating the currently fixated word; rather, it affected where the eyes land on the upcoming word.

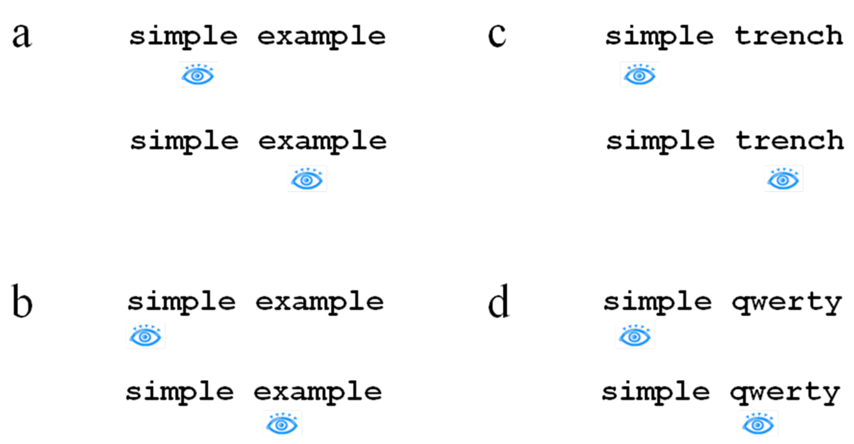

Figure 1.4. Landing positions in active reading. A schematic representation of effects of the distance between the launch site and the gaze location (a and b) and the regularity of the word's beginning letters on the landing position on the word. In a and b, the target word is the same, 'example', but the launch site is closer to the target word in a than b; thus, the eyes fixate the target word 'example' further into the target word in a than b. In c and d, the distance between the launch site and the words are equal but the beginning letters in the target word in c, 'trench', are more regular, or orthographically familiar, than the beginning letters in the target word in d, 'qwerty'; thus, the eyes land closer to the beginning of the target word in d than c. : gaze location.

The results on preview and what affects it (e.g., the load of the fixated word) and what is affected by it (e.g., the landing position on the upcoming word) add to our knowledge about what kinds of information from the fixated word and the next word (i) can be obtained over the course of a fixation and thus (ii) may affect attention. However, similar to the results on the perceptual span (from the moving-window paradigm), the timecourse of these effects are not clear. Nevertheless, given that preview affects where the eyes land (e.g., Hyönä, 1995) and that attention leads the eyes, one could infer that the load of the upcoming word affects attention at least during the orienting phase. The results of Inhoff et al. (2005) suggests that the orienting phase starts between 70 ms and 140 ms into a fixation.

In the moving-window and the boundary paradigms, gaze-contingent display changes usually occur during a saccade (but see Inhoff et al., 2005). Hence, the effects of the change are integrated over the course of a fixation; thus, these paradigms only give us information on the spatial aspects of attention. In order to look at the dynamics of attention, gaze-contingent display changes need to occur during a *fixation* rather than a saccade. In sections 1.2.3.3 and 1.2.3.4, we briefly provide two paradigms that implemented gaze-contingent display changes during a *fixation* in reading.

1.2.3.3 The disappearing-/masked-text paradigms

In the disappearing-/masked-text paradigm, usually the fixated word disappears or is masked after some temporal offset from the beginning of the first fixation on the word (Figure 1.5). In this paradigm, the aim is to find out the time window from the beginning of a fixation during which the availability of visual information from the

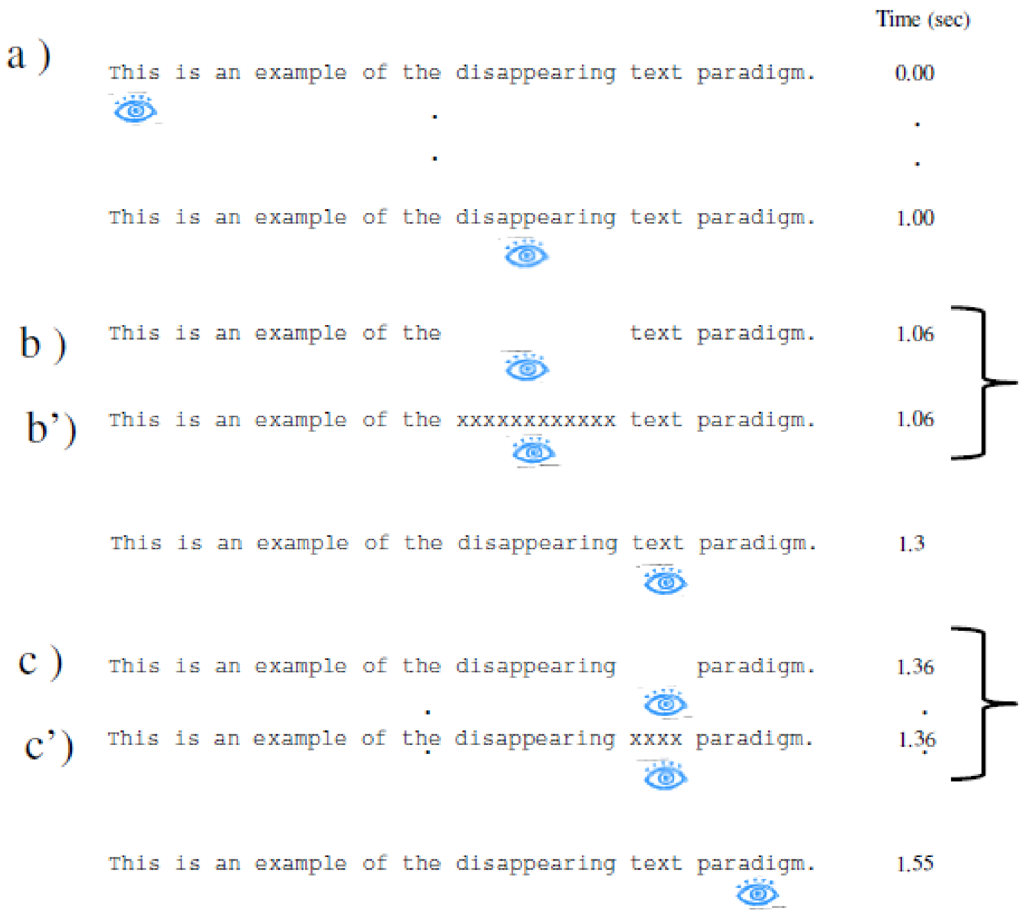

Figure1.5. The disappearing-/masked -text paradigm. A schematic representation of the disappearing/masked text paradigm. In the beginning, letters are all exposed (a); when the eyes fixate on a word for the first time, after about 60 ms from the beginning of this fixation, the fixated word disappears (b,c) in the disappearing-text paradigm or is masked (b',c') in the masked-text paradigm. : gaze location.

fixated word is crucial for fluent reading. One might conclude that at least during this time, attention is engaged with the processing of the fixated word. Thus, the results of this paradigm can inform us about the engagement phase of attention.

In this paradigm, after participants fixate on a (target) word, the letters within a gaze-contingent window disappear (i.e., are replaced by a blank space) or are masked by 'X's (e.g., Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Rayner, Liversedge, & White, 2006; Rayner, Liversedge, White, & Vergilino-Perez, 2003) after a few milliseconds (e.g., 40 - 60 ms) from the beginning of the first fixation on the word.

The results of the disappearing-/masked-text paradigm show that the availability of valid visual information from the fixated word during the first 60 ms or so of a fixation is vital for fluent reading. Thus, attention is engaged with the processing of the fixated word at least during the first 60 ms of the first fixation on the word. In other words, the engagement phase lasts at least 60 ms into a fixation.

Rayner, Liversedge, and White (2006) also showed that the availability of visual information from the *upcoming* word *after* 60 ms into the fixation on the currently fixated word was helpful for reading. Specifically, they manipulated the availability of visual information for the upcoming word. The upcoming word was either present or disappeared, or was masked, *after* 60 ms into the first fixation on the currently fixated word. The authors found that the speed of reading was slower than normal when the upcoming word disappeared/was-masked. One can infer from this result that, some information from the upcoming word (i) is obtained after 60 ms into the current fixation and (ii) is used for the processing of the upcoming word and/or the programming of the upcoming saccade, so that denying this information slows down reading. Thus, after at least 60 ms into a fixation, attention orients towards the next word and/or engages with the next word. In other words, the orienting phase of attention starts after 60 ms into a fixation.

Thus, the disappearing-/masked-text paradigm provides us with some information on the timecourse of attention. However, it is not clear whether this timecourse is affected by the processing load of the fixated word. For example, is the crucial time-window during which the availability of visual information is necessary for reading greater when the fixated word is more demanding? Using the disappearing paradigm, Rayner, Yang, Castelhano and Liversedge (2011) looked at the effects of the frequency of target words on how long the eye fixated on them when the words disappeared/were-masked 40-60 ms into the first fixations on them. Compatible with an earlier study by Rayner, Liversedge, White, and Vergilino-Perez (2003), Rayner et al. (2011) found that the effect of frequency on fixation durations remained even when visual information from these words was only available during the first 40 or 60 ms. Therefore, the first 60 ms of a fixation on a word was necessary and sufficient to extract visual information that was needed for further processing of the word although the speed of reading was reduced compared to normal. Importantly, in Rayner et al. (2011) study, the duration of the window did not depend on the frequency of the fixated word.

In sum, the results of the disappearing-text paradigm suggest that early in a fixation (i.e., during the first 60 ms or so), attention is engaged with the processing of the fixated word. In addition, the results suggest that the orienting phase of attention starts after 60 ms into a fixation. However, the effects of load on attention during the engagement phase and the onset of the orienting phase of attention cannot be inferred. The onset of the orienting phase can be inferred from the results of the switching-text paradigm that is reviewed next (section 1.2.3.4).

1.2.3.4 The switching-text paradigm

In the paradigm we refer to as the switching-text paradigms, the text is switched with another text after some offset from the beginning of each fixation. This technique was introduced by Blanchard, McConkie, Zola and Wolverton (1984) and the aim was to find out whether there is a crucial time window in a fixation during which visual information from the text (i.e., the fixated word) can be utilized for further processing. If the information from the fixated word can no longer be utilized then one can conclude that attention is oriented away from the fixated word. From the results of this experiment, we infer that the orienting phase of attention starts by 120 ms into a fixation in reading.

Specifically, the participant in their study read lines of sentences. For each sentence, there was a pair of words, such as ‘bombs’ and ‘tombs’, that differed in only one letter. Both words fitted the meaning of the sentence and were equally predictable from the sentence; for example, “The underground caverns were meant to house hidden (tombs, bombs), but then the construction was stopped because of lack of funds”. The first target word (the pre-switch target) in this sentence was ‘tombs’; during reading, this target word would be switched to the second target word (the post-switch target) ‘bombs’. This is why we referred to this paradigm as the switching-text paradigm.

A window was defined around the target word in each sentence. This critical window was extended 11 characters to the left and 11 characters to the right of the first letter in the target word. Thus, the window roughly included the target word, the two words that preceded the target word and the word that followed the target word. Only when the eyes were within this window, with some temporal offset (50 ms, 80 ms or 120 ms) from the beginning of *each* fixation, the target word switched into the word it was paired with (e.g., 'tombs' switched to 'bombs'). Hence, in the above example, for a temporal offset of 50 ms, the first target word 'tombs' was shown only during the first 50 ms of each fixation. After 50 ms, the word was masked for 30 ms and, then, was switched with the second target word 'tomb'. During the switch all letters, including the blank spaces, were masked (replaced) by 'X's (see Figure 1.6). Participants pressed a button to read the next line of text until they finished reading the sentence.

When the eyes were outside the critical window, with some temporal offset (50 ms, 80 ms or 120 ms) from the beginning of *each* fixation, the target word (e.g., 'tombs') switched to *itself* (i.e., 'tombs'). Thus, only when the eyes were inside the critical window, the target word switched to its pair (e.g., 'bombs'). Furthermore, to look at the effects of the switch on the eyes, there was a control condition where, for *all* fixations in the text, the text was replaced by 'X's for 30 ms after some offset (50 ms,

Elapsed Time (msec.)

Condition 1	2	3	Display
0	0	0	The underground caverns were meant to house hidden tombs, but then the
50	80	120	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
80	110	150	The underground caverns were meant to house hidden bombs, but then the

Figure 1.6. The switching-text paradigm. After some temporal offset (50 , 80 or 120 ms) from the beginning of each fixation, the whole line of text (including the blank spaces) were masked by Xs for 30 ms. If the eyes were within a critical window that extended 11 characters to the left of the first letter in the target word, here 'tombs', or 11 characters to the right of this letter, the target word would switch to its pair, here 'bombs'. From Figure 1 in Blanchard et al.'s (1984) study.

80 ms or 120 ms) from the beginning of each fixation and then the same text was presented again. Hence, the target word switched to itself for *all* fixations both when the eyes were inside or outside the critical window.

After each sentence, participants were presented with four words that included both the pre-switch and post-switch target words (e.g., ‘tombs’ and ‘bombs’). Participants were asked to indicate which of these four words they had seen in the sentence. They could choose more than one word. The authors were interested to see whether there was an effect of the manipulation of the temporal offset of the switch on the frequency of reporting the first target word (i.e., the pre-switch one), the second target word (i.e., the post-switch one) or both. Figure 1.7 shows their results.

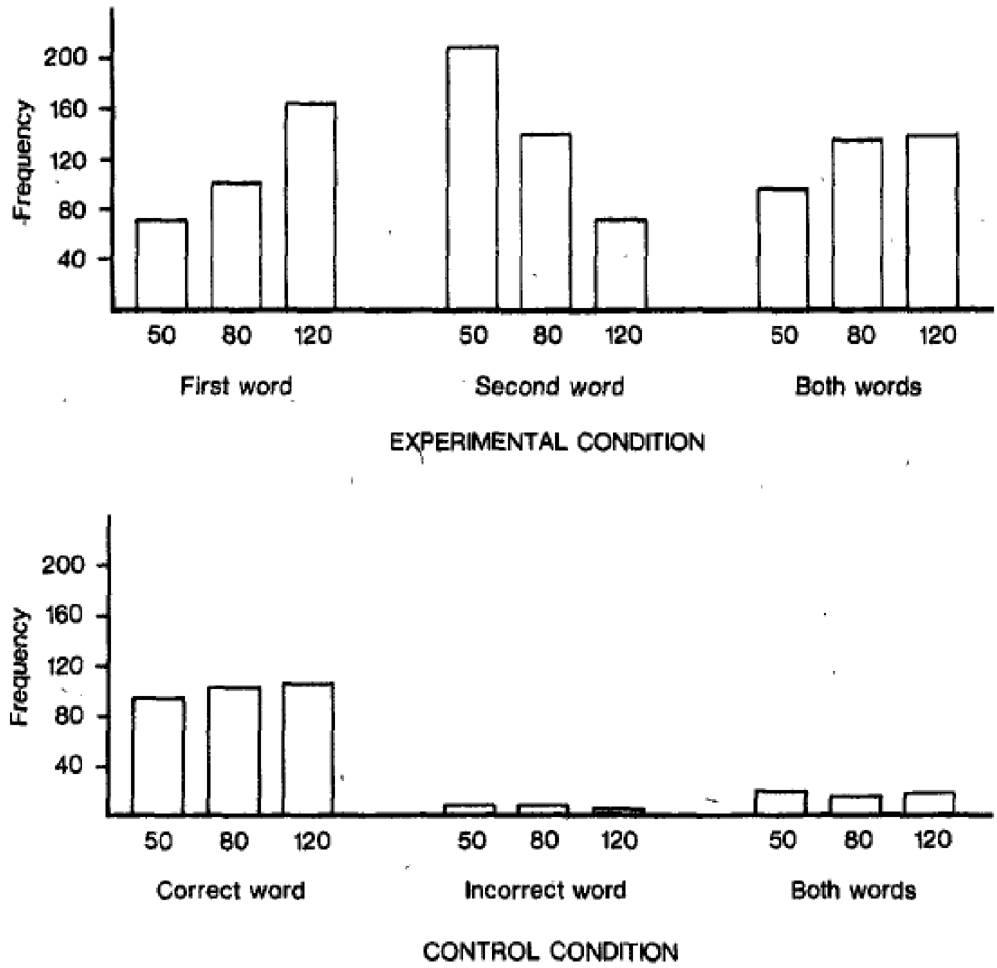

Figure 1.7. Figure 2 in Blanchard et al. (1984). The frequency of reporting the first (pre-switch) target only and the second (post-switch) target only and both targets is shown across different levels of the temporal offset of the switch (50 ms, 80 ms and 120 ms). The

performance is shown for the experimental condition (top panel) and the control condition (bottom panel; where the target word did not switch).

In some trials, participants reported that they saw both target words. In some trials, participants reported only one of the target words, the first (i.e., the pre-switch one) or the second (i.e., the post-switch) one. When both pre-switch and post-switch target words were reported, fixation durations on target words in the experimental condition (where the target word switched) were longer than the control condition (where the target word did not switch). When only one target word was reported, fixation durations in the experimental condition were not different from the control condition. This suggests that when only one of the target words was reported the processing of the other one was not sufficiently advanced for it to be memorized or to affect eye movements. Given that for all temporal offsets both the pre-switch and the post-switch target words could be reported, the authors concluded that the crucial time within which visual information from the fixated word can be utilized is flexible and may vary in each fixation. Therefore, sometimes, only the first word is processed, sometimes, only the second and, sometimes, both.

What is specifically interesting to the purpose of our study in their results is that, when only one word was reported, the probability of that word being the second word (i.e., the post-switch target) decreased with an increase in the temporal offset of the switch. For the temporal offset of 50 ms, the post-switch target word was more likely to be reported whereas, for the temporal offset of 120 ms, the pre-switch target word was more likely to be reported. Our interpretation from this result is that, 50 ms into the fixation, attention was still engaged with the fixated word (compatible with the results of the disappearing/masked text paradigm) and had not oriented away from the gaze location yet. Thus, when the switch occurred, the post-mask target word received sufficient attention and was processed. On the other hand, 120 ms into the fixation, orienting of attention away from the gaze location and towards the next saccadic target may already have started. Thus, when the switch occurred, the post-switch word did not receive sufficient attention for further processing, resulting in less frequent reports of the post-switch target word. In other words, 120 ms into a fixation, the orienting phase had started.

One might expect that attention should orient from the fixated word later when the word is more demanding. This being the case, one would expect that the decrease in the frequency of the report of the second target word with an increase in the temporal offset of the switch would be shallower when the pre-switch target word is more demanding. However, Blanchard et al (1984) did not manipulate the processing load (e.g., the frequency) of the target words.

1.2.3.5 Summary

The disappearing-text paradigm and the switching-text paradigm give us some insight into the timecourse of the engagement and orienting phases. However, the dynamics of attention and the effects of the load of the words on these dynamics remain unclear. The boundary paradigm gives us some insight into effects of the load of the fixated word and the upcoming word on attention but the timecourse of these effects is not clear. The moving-window paradigm gives us some insight into the extent of attention, both on the left and the right side of the gaze location, and the effects of the load of the reading task on the size of the perceptual span, which is an attentional span, but the dynamics of attention and the effects of load on these dynamics remain unclear. While these gaze-contingent display change paradigms can be used to infer some aspects of the dynamics of attention in reading, they are preliminary designed to study the effects of these changes on eye movements. In other words, they do not directly measure attention.

1.3 Measuring attention using word-based stimuli

In section 1.3, we review relevant studies that directly measured attention using word-based stimuli. First, Madrid, Lavie and Lavidora's (2011) study is reviewed. In this study, the authors looked at the effects of the (perceptual) load of a word on the focus of attention around the word, under static viewing condition. This is followed by Doré-Mazars, Pouget and Beauvillain's (2004) study in which, in a single-saccade task, the authors looked at the effects of the orthography of a word on the allocation of attention to the word, shortly before the word is fixated. Then, Fischer's (1999) work is reviewed in detail. Fischer looked at the dynamics of attention, in active reading, using a dynamic-orienting paradigm. Reaction times to detect gaze-contingent probes were the measure of attention in Fischer's study. In the work that we present here, we used a variation of

Fischer's (1999) paradigm in which we used the measure for attention that was more sensitive to the effects of load and the profile of attention in reading. Specifically, we used accuracy of discrimination of a probe, rather than latency of its detection, as the measure of attention. Section 1.4 previews of our own study.

1.3.1 Attention, in static viewing of a word

The effect of the (perceptual) load of the target on the profile of attention around it has been most commonly studied under static viewing conditions (e.g., Brand-D'Abrescia & Lavie, 2007; Caparos & Linnell, 2009, 2010; Hilimire, Corballis, 2011; Lavie, 1994, 1995; Lavie & Tsal, 1994; Lavie, 1995; Linnell & Caparos, 2011); using the flanker paradigm (Eriksen & Hoffman, 1972, 1973, 1974; Eriksen & St. James, 1986) it is concluded that attention is focused on a target more and available to the periphery less when the target has a higher load.

In the flanker paradigm, the extent of the interference of peripheral but response-related flankers on discriminating the target is the measure of attention in the periphery. The idea is that, if the flankers are attended, they will affect target discrimination through response competition (e.g., Eriksen & Hoffman, 1973; Eriksen & St. James, 1986). The more attention the flankers receive the more they interfere with the response to the target.

Traditionally, attention is only measured at one spatial offset from the target (although, see St. James, 1986). Thus, only the amplitude of interference at one location is measured. The conclusion, nevertheless, is that when the processing load of the target is higher, the profile of attention is more narrowly focused around it and this results in a smaller amplitude of attention at a given peripheral location. Thus, in the perceptual load theory, a smaller amplitude of attention in the periphery of the target is interpreted as a narrower focus of attention around the target.

Using the flanker paradigm (Eriksen & Hoffman, 1973), Madrid et al. (2011) showed that attention is focused on a word more when its processing load is higher. Specifically, participants in their study were presented with six-letter strings that made words or non-words. The participant's task was to (i) quickly indicate whether the string contained a target letter 'S' or 'L' and then (ii) indicate whether or not the string made a word (using an unspeeded response). The latter ensured that the meaning of the words was retrieved. Flankers ('S' or 'L') were presented at a fixed peripheral location above or below the centre of the string. String and flanker were presented simultaneously for 200 ms (see Figure 1.8a). The effect of the interference generated by reaction times to discriminate the target was the measure of attention in the periphery.

The strings subtended 2.6 visual degrees in length and 0.4 visual degrees in height. The centre of the string was presented 1.5 visual degrees to the left or to the right of fixation point. Hence, strings covered areas in the foveal and the parafoveal regions, either in the right hemifield or in the left hemifield. The flanker subtended a visual degree of 0.6 vertically and 0.4 horizontally. The distance between the letter string and the flanker letter measured from centre to centre was 1.3 of visual degrees.

The authors manipulated the load of strings by manipulating (i) the hemifield they were shown in, left versus right, and (ii) their lexicality, whether they were words or non-words. Words were always high in frequency. Non-words were made by randomizing the order of the letters in the words while keeping the letter 'S' or 'L' in its original position. It is known that letters can be easily identified when they are embedded in words than in non-words (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; McClelland & Rumelhart, 1981). Thus, the processing load of a string that makes a word is less than that of a string that does not. Additionally, it is known that, for right-handed participants, performance on word recognition tasks (e.g., Hagenbeek & van Stien, 2002) and naming tasks (where participants pronounce the word aloud; e.g., Bub & Lewine, 1988) is better if the word is presented to the right rather than left visual field. This is because stimuli that are in the right visual field are projected to the left hemisphere which is specialized in processing language-related and letter-related information (e.g., Hunter & Brysbaert, 2008). Thus, one would expect that processing of a string of letters that is presented in the right visual field is less demanding compared to that of the one that is presented in the left visual field.

Response times to discriminate target letters were faster when the string made a word than a non-word. In addition, response times were faster when the string was presented in the right than the left visual field. The interference of flankers was greater when the string made a word and was presented in the right visual field. In the right, but not left, visual field, the interference was bigger for words than non-words (see Figure 1.8b).

Madrid et al (2011) suggested that, in the right visual field, attention is focused less on a string that has a lower processing load, under static viewing conditions.

However, the load manipulation for strings in this study was via manipulating (i) the hemifield in which they were presented or (ii) their lexicality (words versus non-words); this is not the way load is usually manipulated in the reading literature (e.g., by manipulating word frequency). In addition, flankers always occurred above or below the strings and thus the results can only be applied to the vertical axis. It remains unclear

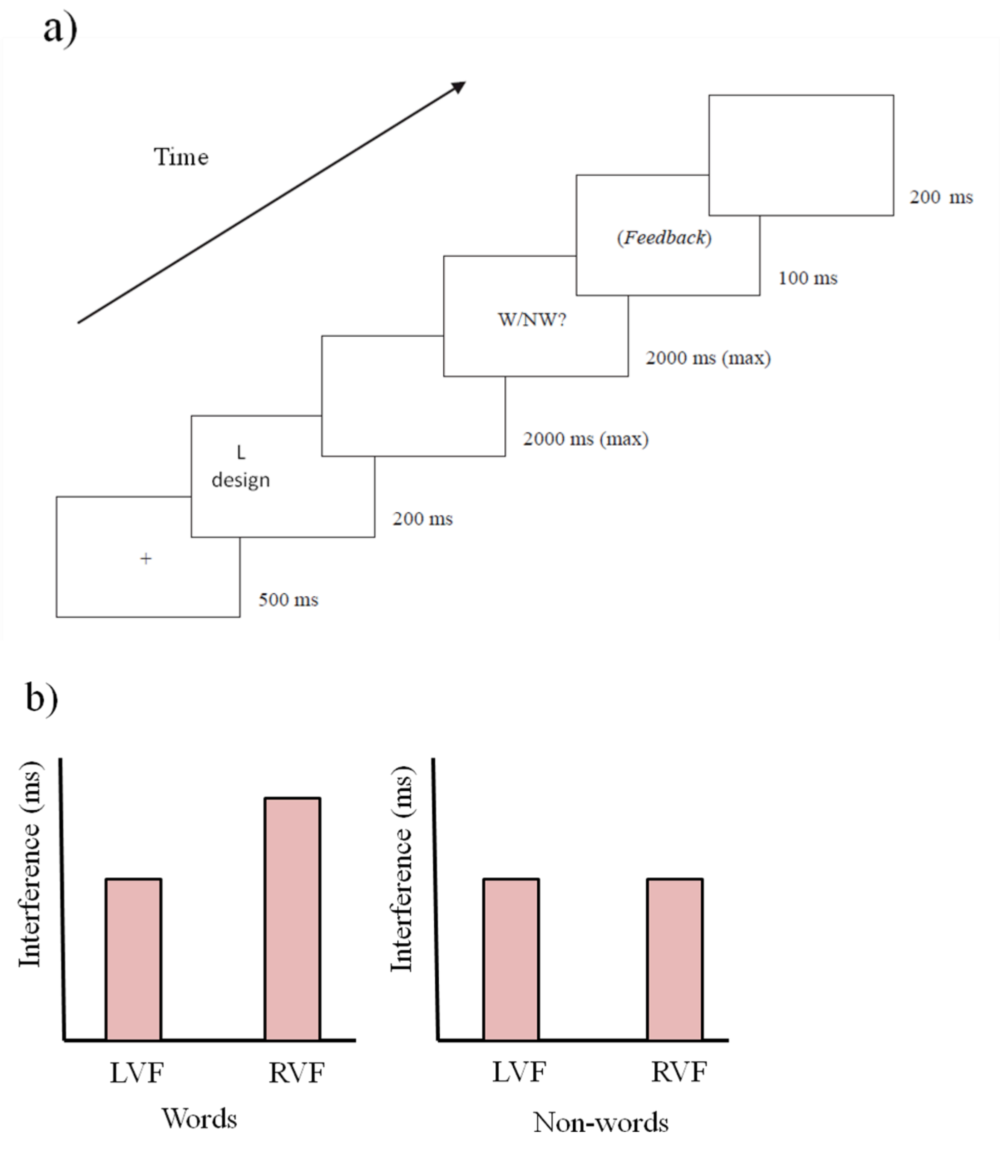

Figure 1.8. Madrid et al.'s (2011) study. (a) A schematic representation of one trial in Madrid et all (2011) study in which the string is presented in the left visual field and makes a word. The target letter is 's' and the flanker ('L') is incompatible with the target (from Madrid et al, 2011, Figure 1). b cartoons the interference of flankers for strings that made words or non-words and were presented in the left or right visual fields (LVF and RVF, respectively). Auditory feedback was provided for both tasks. Response was speeded.

whether attention was also focused more along the horizontal axis, which is generally the axis of interest in reading, when the processing load of a word was higher.

In the work presented here, in Experiments 1, 2, 4 and 5, we looked at the effects of the processing load of the fixated words on attention in active reading.

1.3.2 Allocation of attention to a word just before a single saccade to it

Doré-Mazars et al. (2004) looked at the effects of load of a word on attention, shortly before the word was fixated, in a task that required a single saccade to the word; Thus, they looked at the effect of the load of the to-be-fixated word on the orienting of attention. The authors showed that, shortly before a saccade to a word, the distribution of attention on the word depends on which letter in the word will be fixated: there is more attention closer to the to-be-fixated letter.

Specifically, (French-speaking) participants fixated on a fixation cross at the centre of the screen. The fixation cross then disappeared and, immediately upon its offset, a ten-letter word appeared in the periphery. The letters in the word were masked by dash signs after 220 ms. The first letter in the word was 1.5 visual degrees to the right of fixation. Each letter's width was 0.5 visual degrees. The first bigrams[2] in the words were either legal or illegal, according to (French) writing rules. In 50 % of the trials, there was an increment in the luminance of one letter (2nd or 4th) in the word for 30 ms which occurred with varying SOAs from the offset of the fixation cross. Participants were asked to (i) make a saccade to the word and (ii) detect the luminance change. Only trials in which the change occurred before the participant made the saccade to the word were analysed. The hit rate for detection of the change provided the measure of attention.

The authors showed that, when a saccade was programmed towards the beginning of the word, attention was allocated more to the 2nd than the 4th letter. When a saccade was programmed towards the middle of the word, attention was allocated more to the 4th than the 2nd letter. They only observed this effect of landing position of the eyes (i.e., which letter in a word was going to be fixated) on attention close to the time of the saccade (the last 50 ms before the saccade) but not before that (i.e., 50 ms to 150 ms before the onset of the saccade).

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[2] The combination of two adjacent letters is called a bigram. For example, bigrams in the word 'snowy' are: 'sn', 'no', 'ow' and 'wy'.

The legality of the first bigrams in words did not affect luminance-detection hit rates but did affect where the eyes landed on the word: landing positions were shifted towards the beginning of the word in the illegal compared to the legal condition (about 0.2 characters). Thus, although the results of Doré-Mazars et al.'s (2004) study is in line with attention leading the eyes shortly before the word is fixated and showed an effect of the load of the beginning letters in the word on where the eyes landed on the word, the results failed to reveal an effect of the load of the beginning letters of the word on attention for probes occurring during the last 50 ms It is possible that the load manipulation was sufficiently strong to affect the eyes but not sufficiently strong to affect attention when only a single saccade to the target word was required. In the work presented here (in Experiment 3), we looked at the effects of the load (frequency of the words and the orthographic familiarity of their first trigrams) of the words on attention shortly before they were fixated in active reading, where sequential saccades are required, using a variation of the dynamic-orienting paradigm (Fischer, 1999).

1.3.3 Attention in active reading: the dynamic-orienting paradigm (Fischer, 1999)

Fischer (1999) investigated the distribution of attention, over the course of a fixation, in reading or reading-like tasks. He introduced a dynamic-orienting paradigm where reaction time to detect gaze-contingent probes was the measure of attention at the location of the probe: faster reaction times indexed more attention. Fischer's dynamic-orienting paradigm is of very great importance in bridging the gap between the attentional literature, where performance with a probe is used to index attention directly, and the reading literature, where eye movements are used to make inference about attention.

Specifically, for the primary task, the participant in his study either (i) performed a reading-like search task on letter-strings or (ii) read a text for comprehension or (iii) just scanned through a pseudo-text without vowels (Figure 1.9). For the search task, in each trial, participants were asked to search for target letters (K, V, H, O) that were embedded in strings of 'X's. The strings of 'X's were made by changing all the letters in a line of text into Xs. In 50 % of the trials, there was a target letter in one string. For the reading task, participants read a text for comprehension and were occasionally asked a comprehension question about the sentence they had just read. For the scanning task, participants were instructed to move their eyes from left to right through a pseudo-text as if they were reading. The pseudo-text was made by replacing vowels with consonants.

For the secondary task, the participant was asked to make speeded detections of gaze-contingent abrupt-onset probes (asterisks) that appeared briefly (for 30 ms) above a character in the line of text/strings-of-letters after the beginning of the first fixation on an unpredictable target word/string in each sentence/string-of-letters (from the left, the fourth string of letters in each line in Figure 1.9a, b and c). In the reading task, target words were either low or high in frequency.

The probe occurred at various spatial offsets (5, 10 characters) to the right or left of the gaze location or at the gaze location (at a spatial offset of 0 characters). It occurred with either 25 ms or 170 ms temporal offset from the beginning of the first fixation on the target word/string. Probes with spatial offsets of 10 characters occurred 3.3 visual degrees from the gaze location.

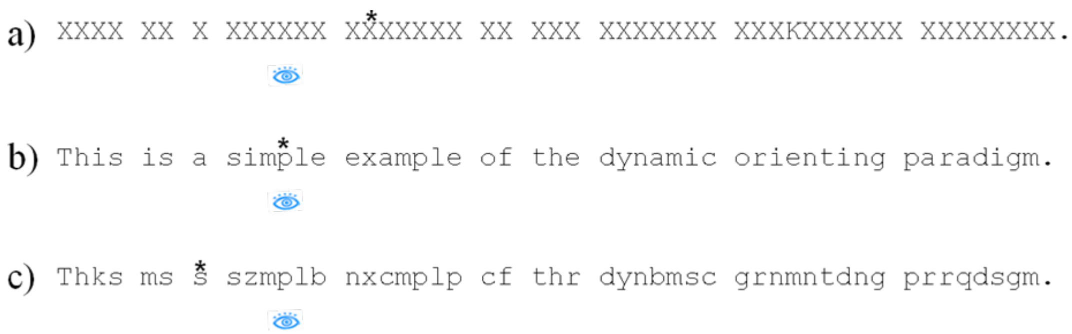

Figure 1.9. Fischer's (1999) study. A schematic representation of one trial where the probe occurred with a spatial offset of +5 characters from the gaze location in the search task (a), a spatial offset of 0 characters in the reading task (b), and a spatial offset of -5 characters in the scanning task (c).

* the probe : gaze location.

1.3.3.1 Attentional results in Fischer's (1999) study

For all tasks, trials were analysed only if the probe-onset occurred within a single fixation on the target word/string and this single fixation was followed by a forward saccade to the next word/string. In addition, in the search task, only trials where there was no target letter (i.e., K, V, H, or O) in the string of letters (50 % of the trials) were analysed. Reaction times (RTs) to detect the probe were used as a measure of attention: faster RTs indicated more attention at the probe location. The results are provided in Figure 1.10. In the search task, for temporal offsets of 170 ms, but not 25 ms, RTs were faster 5 characters to the right of the gaze location than the left. The author concluded that 170 ms into the fixation, attention was allocated more to the right than the left of the gaze location. This was evidence that attention was orienting ahead of the eyes (i.e. towards the next saccadic target) by 170 ms into the fixation.

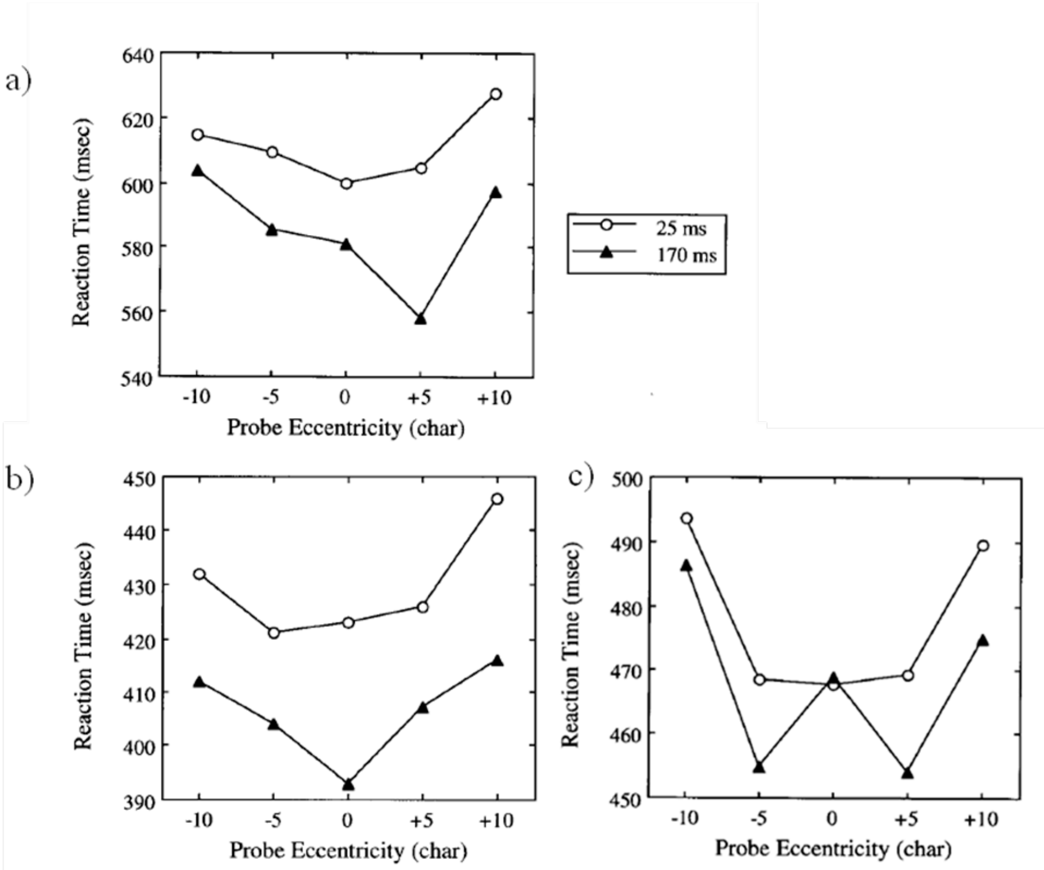

Figure 1.10. Fischer's (1999) results on attention. Fischer's (1999) results on mean reaction times to detect the probe as a function of the eccentricity (spatial offset) of the probe from the gaze location in (a) the search, (b) the reading and (c) the scanning tasks. Performance is broken down for temporal offsets of 25 ms (open circles) and 170 ms (filled triangles). From Figures 1, 2, and 3 in Fischer (1999).

In the reading task, frequency of target words was manipulated to be high or low. While there was an effect of frequency on the duration of single fixations on target words, there was no effect of frequency on probe-detection RTs. Therefore, Fischer reported results that were pooled across word frequency. Reaction times were faster for temporal offsets of 170 ms than temporal offsets of 25 ms, regardless of the location of the probes. The author concluded that attention was engaged more with the processing of the fixated word 25 ms than 170 ms into a fixation. However, 170 ms into the fixation, there was no difference between RTs for probes that occurred to the left and to the right of the gaze. The results of the scanning task also did not reveal any difference between probes occurring on the left or right side of the gaze location.

In sum, Fischer found an asymmetry in the profile of attention, late in a fixation, (i.e., at temporal offsets of 170 ms) for the search task consistent with an orienting of attention, late in a fixation, towards the next saccadic target. However, his results did not reveal an asymmetric profile of attention around the gaze location or any effects of load (i.e., word frequency) on attention for the reading task.

1.3.3.2 Did the probe affect reading and/or the eyes?

If reading occurred (i.e., words were processed at lexical levels) the effect of frequency on fixation durations should be preserved. This is because the frequency of a word affects the time that the eyes fixate on the word only if reading occurs (Rayner & Raney, 1996). In Fischer's (1999), fixation durations were longer on low- than high-frequency words. Thus, reading occurred. However, the probe, as an abrupt-onset stimulus, affected the programming of the upcoming saccade (e.g., Findlay & Walker, 1999; Walker, Deubel, Schneider & Findlay, 1997). We note that any display change during reading is expected to affect the eyes; for example, fixation durations are prolonged in the disappearing/masking text paradigm (e.g., Rayner et al., 2003).

To have a baseline for the undisrupted behaviour, for the reading task, the probe only occurred in 50 % of the trials in some blocks of the experiment in Fischer's (1999) reading task. For these blocks, the probe-present and probe-absent trials were intermixed. The average duration of single fixations on target words were 318 ms and 305 ms on low- and high-frequency words, respectively, in the probe-present condition, and 286 ms and 273 ms, respectively, in the probe-absent condition. Hence, the probe prolonged fixations but the effect of frequency on the duration of single fixations was independent of the probe. In other words, the probe did not interrupt the processing of the fixated word at lexical levels, confirming that reading occurred.

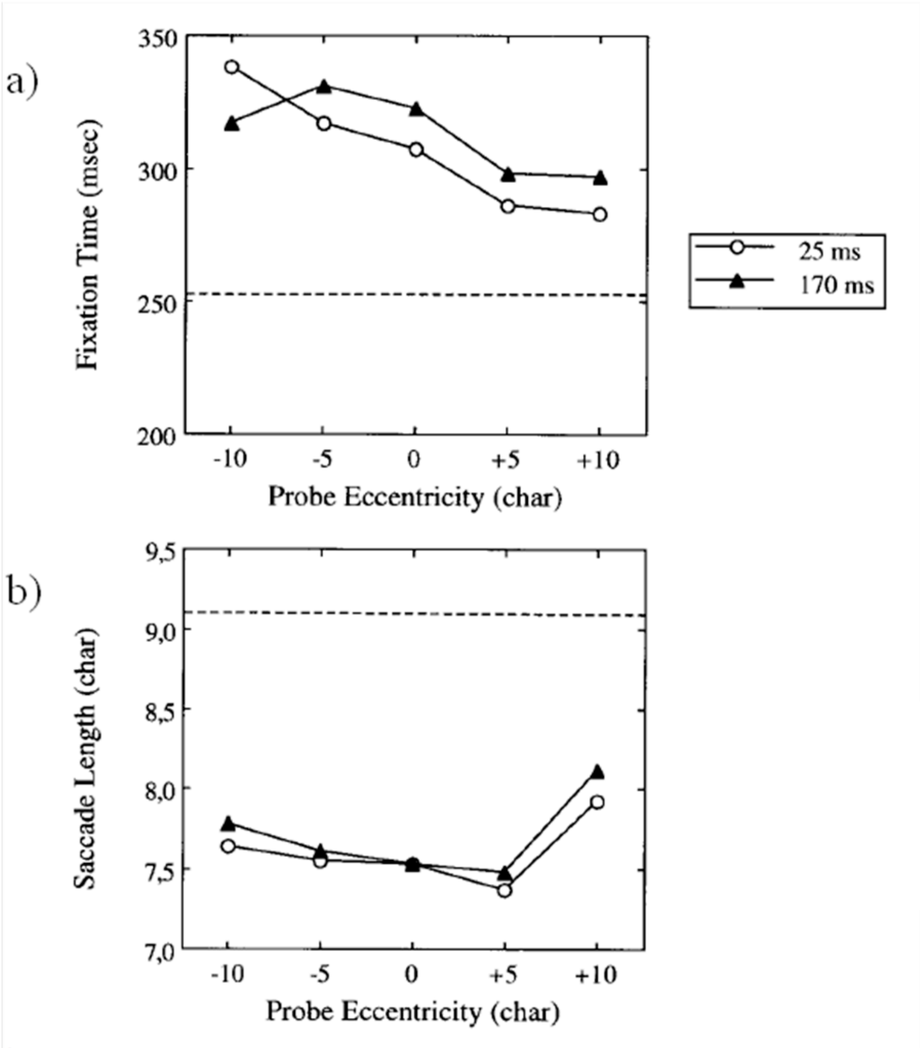

Figure 1.11. The effects of the probe on eye movements in Fischer's (1999) reading task. The average duration of single fixations (a) and the average saccade length from these fixations (b) in Fischer's (1999) reading task, as a function of the spatial offset of the probe. Performance is broken down for temporal offsets of 25 ms (open circles) and 170 ms (filled triangles). Hatched lines show baseline performance, that is, when there was no probe. From Figure 3 in Fischer (1999).

The probe affected the length of the upcoming saccade in addition to the timing. Saccade lengths from the target word to the next word decreased in the probe-present (mean = 7.6 characters) compared to the probe-absent (mean = 9.1 characters) condition. Fixations were prolonged more and saccades were shortened less for probes occurring on the left than the right side of the gaze location (Figure 1.11). For probes occurring in the right hemifield (i.e., in the direction of reading), saccades were shortened less for probes with a spatial offsets of 10 characters compared to 5 characters. This was presumably because probes occurring with a spatial offset of 10 characters were closer to the intended saccadic location (i.e., 9.1 characters in the absence of the probe) and attracted the eyes more and thus shortened saccades less.

While the spatial offsets of the probes did affect the decision on exactly when/where to move the eyes, the temporal offset of the probe did not. There was no difference between temporal offsets of 25 ms and 170 ms in terms of fixation durations and saccade lengths. Given that there are separate routes that are responsible for the timing of saccades (i.e., 'when' to make a saccade) and the metrics (i.e., 'where' to make a saccade) (Van Gisbergen, Gielen, Cox, Bruijns, & Kleine Schaars, 1981), the probe may affect the timing and the metrics of the upcoming saccade differently.

1.4 Our study

In Fischer's (1999) reading task the effect of frequency on fixation durations was preserved; thus, reading occurred. However, there was no evidence of an orienting of attention in the reading task. We believe that although the probe in Fischer's (1999) study was sensitive to the profile of attention in a search task, it was not sufficiently sensitive in a reading task (Reichle, Vanyukov, Laurent, & Warren, 2008). We, therefore, adopted a new version of the paradigm using a more sensitive probe to investigate the dynamics of attention and the effects of load in reading.

Our study addresses the dynamics of attention and the effects of load on these dynamics, over the course of a fixation, in a reading task. We used a secondary task adapted from the dynamic-orienting paradigm (Fischer, 1999) to probe attention at the gaze location and 6 characters on the right or left side of the gaze location with varying temporal offsets from the beginning of the first fixation on target words. The version of the dynamic-orienting paradigm that we used is introduced in section 1.4.1, followed by a summary of our assumptions and predictions in terms of attention (section 1.4.2) and the effects of the probe on eye movements (section 1.4.3). Then, finally, we provide an outline of the experimental chapters in section 1.4.4.

1.4.1 Our technique, adapted from the dynamic-orienting paradigm (Fischer, 1999)

The secondary task, in our study, was unspeeded discrimination of the orientation of the probe, rather than the speed of its detection. We expected that the probe would be more sensitive to the profile of attention in reading by requiring discrimination rather than detection (Sagi & Julesz, 1984). Unspeeded discrimination of the orientation of a probe has been shown to be sensitive to the profile of attention in a task that required sequential eye movements (Gersch, Kowler, Schnitzer & Dosher, 2008).

The probe was a tilted line slanted 22.5 visual degrees to the right or left of the vertical meridian. It was brighter than the text and was briefly, for 30 ms, superimposed on a character in the text. Probe discrimination accuracy was the measure of attention: higher accuracy indexed more attention.

In order to look at the effects of the load of words on attention, we had a *target* word in each line of text and manipulated the load of this target word. The target word was either high or low in frequency, in all experiments. In addition, the orthographic familiarity of the first trigrams in target words was either high or low in Experiments 3, 4 and 5. The target word was not predictable from the context. In addition, it was written in the same format as other words and could occur in a range of locations around the midline of the text. Thus, there was no visual or locational cue to the target word.

In each trial, the probe occurred either at the gaze location (central probes) or 6 characters to the left (left probes) or 6 characters to the right (right probes) of the gaze location. The probe occurred with varying temporal offsets relative to the first fixation on a *critical* word, Wn, in the line of text. The results of the boundary paradigm (Rayner 1975a, 1975b) indicate that both the fixated word, Wn, and the upcoming word, Wn+1, can be processed when the eyes are still on the fixated word. Therefore, the distribution of attention on the gaze location may be affected by the load of the fixated word and/or the upcoming word. In most of the experiments reported here (Experiments 1, 2, 4 and 5), we looked at the effects of the load of the 'fixated word' on attention. Thus, the target word (i.e., the word that we controlled its processing load) was Wn (i.e., the word that was fixated when the probe occurred) in these experiments. In one Experiment (i.e., Experiment 3), we looked at the effects of the load of the upcoming word on attention. Thus, the target word was Wn+1 (i.e., the upcoming word) in Experiment 3. Figure 1.12 shows a schematic illustration of one trial in which the target word was Wn.

Before we provide our assumptions and predictions in terms of attention, it should be noted that the probe - as an abrupt-onset stimulus- was expected to affect the eyes. Nevertheless, given the results of Fischer's (1999) study, we expected that the probe

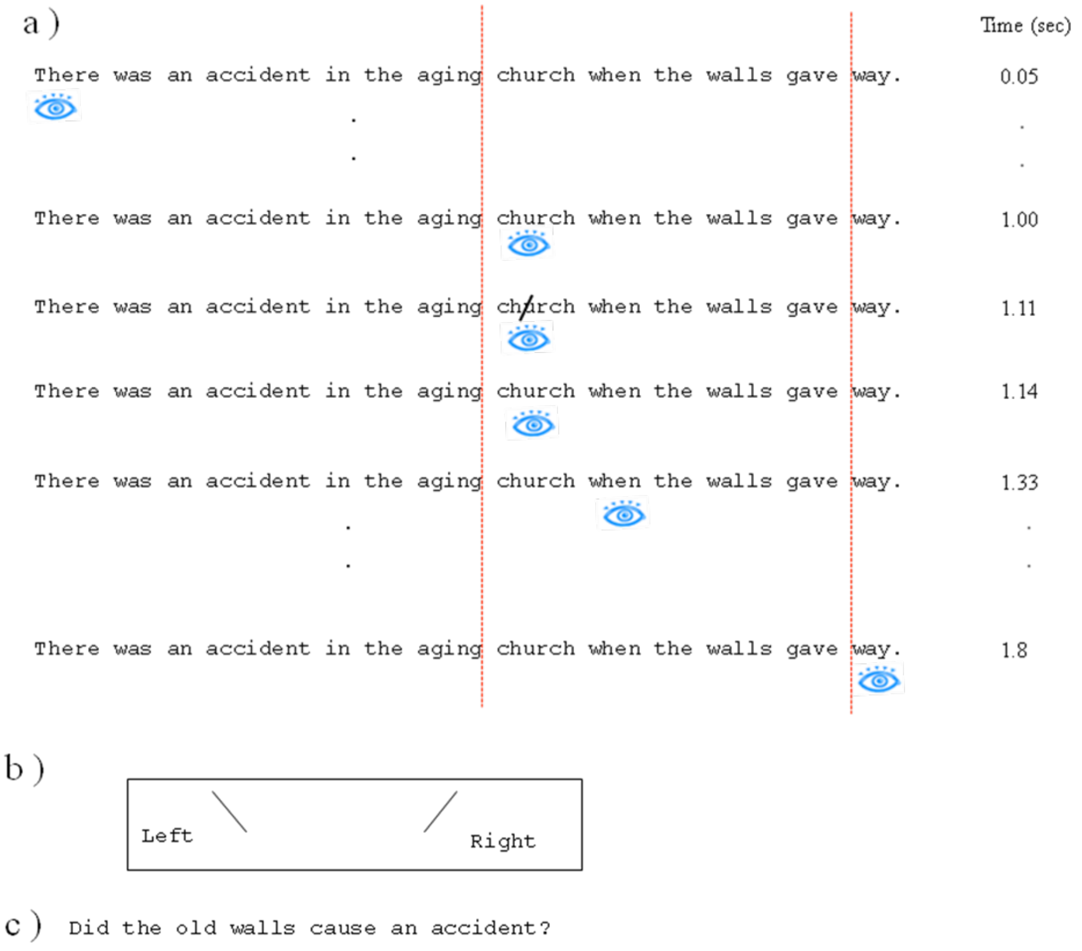

Figure 1.12. A schematic representation of one trial in our study. One sentence at a time was presented on the screen (a). The participant read each sentence in silence. There was a target word, here the word ‘church’, embedded in each sentence. The frequency of the target word was either high or low; here the frequency of ‘church’ is high. When the participant’s eyes crossed an invisible boundary to the left of the target word (the first vertical line from the left; the red lines are shown for illustration purpose only), after some temporal offset from the beginning of the first fixation (here a temporal offset of 110 ms), the probe occurred, here with a spatial offset of 0 characters. The probe was only presented for 30 ms. Participants were asked to (i) try not to be distracted by the probe and (ii) continue reading. Participants read each sentence only once. When their eyes crossed an invisible boundary close to the end of the sentence (the second vertical line from the left), the sentence disappeared after 400 ms. After the sentence disappeared, another screen appeared asking about the orientation of the probe (b). After the response to the probe was made, in 25 % of the trials, another screen appeared asking participants to verbally answer (‘yes’ or ‘no’) a comprehension question concerning the sentence they had just read (c).  : gaze location.

would not disturb the processing of words at lexical levels. Thus, we expected longer durations for first fixations on target words that were low rather than high in frequency. Throughout the thesis, we provide results on how the probe affected fixation durations and saccade lengths and briefly discuss these results (i) to demonstrate that reading occurred and (ii) for completeness. Nevertheless, the way in which eye movements are affected by the probe is not the main focus of this thesis. Rather, accuracy on the performance on the probe, as the measure of attention, is our main interest. Thus, the design and flow of the experiments are guided by results from probe-discrimination accuracy. Section 1.4.2 provides our assumptions and predictions on the dynamics of attention during the course of a fixation in reading.

1.4.2 Our assumptions and predictions concerning attention

Following Morrison (1984) who proposed attention is first centred on the fixated word and then shifts towards the next word in order to select the location for the upcoming saccade, we assumed two phases for attention over the course of a fixation: the *engagement phase* and the *orienting phase*.

We proposed that the fixation begins with *the engagement phase*. During this phase, attention is engaged with the processing of the *fixated* word. This is compatible with the results of the disappearing-/masked-text paradigm (e.g., Rayner et al., 1981, 2003, 2006) that the availability of visual information from a word is crucial for the first 60 ms or so of a fixation. By halfway through a fixation, we proposed that attention should be free to orient towards the next word. This is presumably when the *orienting phase* starts. This is in line with the results of the switching-text paradigm (Blanchard et al., 1984) which suggest that by 120 ms into a fixation the orienting of attention from the fixated word has started. The orienting phase lasts up until the end of a fixation. During the orienting phase, we proposed that attention (i) orients way from the fixated word and (ii) engages with the upcoming word if the upcoming word is fixated next.

Sections 1.4.2.1 and 1.4.2.2 cover our predictions, in terms of attention, for the engagement and orienting phases respectively.

1.4.2.1 The engagement phase

We analysed probes occurring early in a fixation for the engagement phase. However, we did not analyse central probes for this phase. Central probes occurring early in a fixation may interfere with processing of the fixated word. This is because central probes occupy the same spatial location as the fixated word. Given that during the engagement phase, valid visual information from the fixated word is necessary for fluent reading (e.g., Rayner et al., 1981, 2003, 2006), detecting a central probe may lead to some decoding conflict between the fixated word and the probe. Therefore, for the engagement phase, we only analysed trials in which the probe occurred in the periphery (i.e., left and right probes).

We expected that attention would be centred on the gaze during the engagement phase and equally available on the left and the right side of the gaze (i.e., symmetric around the gaze). This is because we did not expect attention to have oriented towards the next saccadic target during the engagement phase. Thus, we did not expect an effect of the spatial offset of the probe on its discrimination.

We predicted that, during the engagement phase, attention would be focused on the gaze more for high- than low-frequency words. As Morton (1969) suggested, low-frequency words demand more attentional resources for encoding information than high-frequency words. Thus, we expected that attention would be more narrowly focused on words that are low rather than high in frequency. This is in line with a more focused attention on words with higher processing load in static viewing conditions (e.g., Madrid et al. 2011). More focused attention should result in poorer discrimination for probes occurring 6 characters from the gaze location.

Given that we only probed attention at one spatial offset from the gaze, on each side of the gaze location, we could not measure the focus of attention directly; rather we inferred focus from the amplitude of attention 6 characters from the gaze location. This is compatible with the assumptions of the flanker paradigm where a greater amplitude of attention in the periphery is interpreted as a wider focus of attention (e.g., Lavie, 1994, 1995; Madrid et al., 2011). Thus, through out the thesis, for the engagement phase, we interpret the amplitude of attention in the periphery (i.e., 6 characters to the left or right of the gaze location) as an indicator of the focus of attention: the smaller the amplitude the more focused the attention.

The effects of the frequency of the fixated word on the focus of attention, during the engagement phase, were investigated in Experiments 1 and 2, in which participants were tasked to read sentences, and in Experiments 4 and 5, where participants were tasked to read strings of random words (see Table 1.1 for an of outline of the experiments).

The reading task affects the processing load of a word. Presumably, this is partly because the perceptual span is narrower when the reading task is more demanding (Häikiö et al., 2009; Inhoff et al., 1989; Rayner, Murphy, Henderson, & Pollatsek, 1989) and the size of the span is suggested to affect preview (e.g., Henderson and Ferreira , 1990; Häikiö et al., 2010). To address whether the reading task modulates any effects of word frequency on the focus of attention, during the engagement phase, the reading task was 'reading strings of random words' rather than 'reading sentences' in Experiments 4 and 5. We expected that any effects of frequency on the focus of attention would be weaker where the reading task is 'reading strings of random words' rather than 'reading sentences', given that the former is a harder tasks results in less preview of the word before it is fixated.

We addressed whether or not having a valid preview of a word affects the focus of attention, early during the first fixation on the word, directly in Experiment 5 where preview of words was invalid. In the absence of valid preview, we expected that, very early in a fixation, the frequency of the fixated word should not affect attention. This is because, without valid preview, the processing of words should not be sufficiently advanced to reveal any effects of frequency on attention, very early in a fixation (e.g., 10 to 40 ms into a fixation).

1.4.2.2 The orienting phase

The engagement phase lasts until about halfway through a fixation (e.g., about 110 ms or so; inferred from the results of Blanchard et al., 1984). Then the orienting phase starts. We expected that, from half way through a fixation, up until the end of a fixation, attention should orient towards the next saccadic target (i.e., towards the right in western texts). Valid visual information from the fixated word is not necessary for fluent reading, during the orienting phase, for the task of reading sentences (Rayner et al., 1981, 2003, 2006). Therefore, during the orienting phase, we probed the participant's attention at the gaze location (at spatial offsets of 0 characters; central probes) as well as in the periphery (6 characters on the left or right of the gaze location) when the participant read sentences for comprehension.

We proposed that, during the orienting phase, attention would increase on the right side of the gaze (i.e., at spatial offsets of +6) and decrease elsewhere (i.e., at spatial offsets of 0 and -6 characters). Furthermore, we expected that the orienting of attention would start earlier when the fixated word was high rather than low in frequency. This is because Henderson and Ferreira (1990) found a bigger preview benefit for the upcoming word when the fixated word was high rather than low in frequency suggesting a wider perceptual span on the right side of the gaze for the former. In addition, fixation durations are shorter on high- than low-frequency words (Rayner, 1998; Reingold et al., 2010; Sereno, 1992; Staub et al., 2010) in active reading; given that attention always leads the eyes (e.g., Gersch et al., 2008), this suggests that the orienting of attention occurs earlier for high- than low-frequency words.

Thus, we expected to see that, over time, discrimination of probes occurring on the right side of the gaze (i.e., at a spatial offset of +6 characters) improved and discrimination of probes occurring elsewhere (i.e., at spatial offsets of 0 and -6 characters) worsened. In addition, we expected that the above improvement/worsening should occur earlier when the fixated word was high rather than low in frequency. Thus, we expected an interaction between spatial and temporal offsets of the probe and word frequency. In Experiments 1 and 2, we investigated the timecourse of the orienting of attention and the effects of the frequency of the fixated word on that timecourse.

In addition, we expected that the processing load of not only the fixated word but also the upcoming word would affect attention, over the course of a fixation. This is because the properties of not only the fixated word (e.g., its frequency) but also the property of the upcoming word (e.g., its orthography) affect eye movements in reading. Thus, attention should be engaged with the processing of the upcoming word before the eyes fixate it. The processing of the upcoming word is sufficiently advanced to affect where the eyes land on the word (e.g., White & Liversedge, 2004a, 2004b, 2006): the more demanding is the processing of the upcoming word, the closer the eyes land to the beginning of the upcoming word.

We proposed that the more demanding is the processing of the upcoming word, the more attention should be allocated to it and the less attention should remain at the gaze location. In other words, shortly before a saccade to the upcoming word, we expected to see poorer discrimination of probes occurring at the gaze location when the processing of the upcoming word was more demanding. In Experiment 3, we manipulated the processing load of the upcoming word, by manipulating its frequency and the orthographic familiarity of its first trigram, and investigated the effect of the load of the upcoming word on attention during the orienting phase.

1.4.3 Our assumptions and predictions concerning eye movement behaviours

The probe, as an abrupt-onset stimulus, was expected to delay the upcoming saccade (e.g., Findlay & Walker, 1999; Fischer; 1999; Walker et al., 1997). Nevertheless, an effect of frequency on fixation duration would confirm that reading occurred given that fixations are longer on low- than high-frequency words only when reading occurs (Rayner & Raney, 1996). Thus, we expect an effect of frequency on the duration of the first fixation on target words during both engagement and orienting phases.

It should be noted that programming of a saccade is known to happen in two stages: a labile stage and a non-labile stage (Becker & Jürgens, 1979). During the labile stage, a saccade can be cancelled or its metrics can be changed. During the non-labile stage, the saccade's metrics can no longer be changed or cancelled and the saccade will be executed. Thus, we expect that the probe should affect the metrics/timing of the upcoming saccade when it occurs during the labile, rather than non-labile, stage of saccade programming. In line with this, Reingold and Stampe (2000, 2004) showed that any display change during reading reduces the frequency of saccades only after about 70 ms from the onset of the change. This is because a display change that occurs late in a fixation is likely to occur during the non-labile stage of saccade programming. Thus, we conclude that changes occurring late in a fixation should prolong fixations less than changes occurring halfway through a fixation. As a result, we expected an effect of the temporal offset of the probe on fixation durations during the orienting phase.

Furthermore, given that the results of Fischer's (1999) study showed no difference between early (temporal offsets of 25 ms) and late probes, in terms of fixation durations, we expected that probes occurring early during the fixation should prolong the fixations less compared to probes occurring half way through a fixation. As a result, we expected an effect of the temporal offset of the probe on fixation durations during the engagement phase.

In addition to an effect of temporal offset, we expected an effect of spatial offset on fixation durations. In Fischer's (1999) study, the duration of single fixations was longer when the probe occurred on the left than the right of the gaze location. In line with this, Reingold and Stampe (2000, 2004) showed that, when the size of the display change was small, the increase in fixation durations was bigger for changes that occurred in the opposite direction of the intended saccade. Thus, we expected longer fixations for probes occurring on the left than right.

In addition to the timing of the upcoming saccade, we expected that the probe would also affect its metrics. Given that the average saccade lengths is between 7 and 9 characters in reading English texts (e.g., Fischer, 1999; Rayner, 1978; Rayner, McConkie, & Ehrlich, 1978), a probe occurring 6 characters to the right of the gaze is close to the intended saccadic target, and thus is likely to attract the eyes. In addition, it is known that the decision on the direction of a saccade is made prior to the decision on its length (Hou & Fender, 1979). Therefore, a right probe is more likely to affect the length of a rightward saccade than a left probe. Hence, we expected an effect of the spatial offset of the probe on saccade lengths.

Similar to our predictions for the effects of the temporal offsets of the probe on fixation durations, we expected that probes occurring halfway through a fixation would affect the metrics of the upcoming saccade more than those occurring early or late in a fixation. Thus, we expected an effect of the temporal offset of the probe on saccade lengths during both engagement and orienting phases.

In sum, we expected that the probe, as an abrupt-onset stimulus, would prolong fixation durations and shorten saccade lengths. Nevertheless, we expected that reading would be preserved as indexed by an effect of frequency on fixation durations. In the following section 1.4.4, we briefly outline the experimental chapters.

1.4.4. Outline of the experimental chapters

Each chapter begins with an introduction section in which we outline our assumptions and predictions in terms of the effects of the experimental manipulations on probe discrimination as the measure of attention. We follow this with our predictions in terms of the effects of the probe on fixation durations and saccade lengths. In the results section, the results for (i) accuracy on probe discrimination, (ii) the duration of first fixations on target words and (iii) the length of forward saccades from these first fixations are provided, separately, for both the engagement and orienting phases. The statistical analyses are based on ANOVAs. In the discussion section, we discuss the results on attention followed by a brief discussion on the effects of the probe on eye movements.

In Experiments 1 and 2 (chapters 2 and 3, respectively), we looked at the effects of the frequency of the fixated word on attention, during both the engagement phase (i.e., temporal offsets of 10 to 110 ms) and the orienting phase (temporal offsets of 110 to 220 ms). In Experiment 2, in some trials, there was no probe. These control trials provided a baseline for fixation durations and saccade lengths (see Table 1.1).

In Experiment 3 (chapter 4), we investigated the effects of the processing load of the target word on the orienting of attention from the word that preceded the target word. We manipulated the target word's frequency and the orthographic familiarity of its first trigram. In each trial, we probed attention at the gaze location during the last 100 ms of a single fixation on the word that preceded the target word.

In Experiment 4 (chapter 5), we changed the task from reading sentences to reading strings of random words. We looked at the effects of the reading task on attention, during the engagement phase. The results of this experiment were compared with the results of Experiment 1, where the participant's task was to read sentences.

In Experiment 5 (chapter 6), we addressed whether the validity of preview modulates the focus of attention during the engagement phase. The participant's task was to read strings of random words with an invalid preview. The results of this experiment were compared with the results of Experiment 4, where preview was valid.

Experiment	**Reading task**	**Preview**	**Target word**	**Engagement phase**	**Orienting phase**	**Control trials**
1	sentences	valid	Wn	+	+	--------
2	sentences	valid	Wn	+	+	+
3	sentences	valid	Wn+1	--------	+	--------
4	words	valid	Wn	+	--------	--------
5	words	invalid	Wn	+	--------	--------

Table 1.1. Outline of the experiments. The engagement phase of attention (i.e., temporal offsets of 110 ms or smaller) was studied in Experiments 1, 2, 4 and 5. The orienting phase of attention (i.e., temporal offsets of 110 ms and bigger) was studied in Experiments 1, 2 and 3. Control trials in which the probe did not occur were included in Experiment 2, to serve as a baseline for fixation durations and saccade lengths. For Experiments 1, 2 and 3, participants' primary task was to read sentences for comprehension. For Experiments 4 and 5, participants' primary task was to read strings of random words. Participants received valid preview of the upcoming word in all experiments except Experiment 5. The probe occurred when the eyes landed on a Wn in each sentence or string of words. There was a target word in each sentence or string of words. This target word was either Wn (in Experiments 1, 2, 4 and 5) or the word that followed Wn (i.e., Wn+1; in Experiment 3). The effects of the load of the target word on attention was investigated by manipulating its frequency (in all experiments) and the orthographic familiarity of its first trigram (in Experiments 3, 4 and 5).

Chapter 2

Effects of the load of the fixated word on the dynamics of attention

2.1 Introduction

In Experiment 1, we investigated the dynamics of attention during the course of a fixation in reading and whether, and if so how, these dynamics are affected by the load of the fixated word. We manipulated the load of target words by manipulating their frequencies to be high or low. We used a dual-task paradigm adapted from Fischer's (1999) study to probe attention while the eyes were fixating on target words.

We assumed two phases for attention during the course of a fixation: the engagement and orienting phases. During the engagement phase, we proposed that attention would be focused on the gaze location but more when the fixated word was more demanding. During the orienting phase, we expected that attention would orient towards the to-be-fixated location and away from the already-fixated locations, but earlier when the fixated word was less demanding.

In line with Morrison (1984), we assumed that early in a fixation (i.e., during the engagement phase), attention would be centred on the gaze. Given that (i) processing of a word starts while the eyes are still on the preceding word; that is, the word is previewed before being fixated (Rayner 1975a, 1975b) and (ii) the word's processing is integrated across the saccade to the word (e.g., Inhoff, Starr, & Shindler, 2000; Rayner & Clifton, 2009) we expected that early in a fixation processing of the word should be sufficiently advanced to reach those levels that correspond to the word's frequency. Thus, we expected an effect of frequency on attention, early in a fixation. Specifically, we proposed that attention would be focused on the gaze location more when the fixated word was low rather than high in frequency. This is because, from perceptual load theory, it is known that attention is focused more on a target with a higher load (Brand-D'Abrescia & Lavie, 2007; Caparos & Linnell, 2009, 2010; Lavie, 1995; Linnell & Caparos, 2011, Madrid et al., 2011). Given that a word demands more attention both when its perceptual load is high (e.g., Madrid et al., 2011) and when its frequency is low (e.g., Morton, 1969), we proposed that when the fixated word is low rather than high in frequency, attention would be focused more on the gaze location. Thus, at a given distance from the gaze location, the amplitude of attention should be smaller for low- than high-frequency words, during the engagement phase of attention.

We proposed that the orienting phase would start halfway through a fixation. This is supported by the results of the switching-text paradigm (Blanchard et a., 1984). The results of the switching-text paradigm showed that if the fixated word switched to another word, after 120 ms into a fixation, the post-switch word might not be processed. Thus, we proposed that, from halfway through a fixation, the orienting of attention towards the next saccadic target starts. We expected that orienting of attention towards the next target should be slowed down or delayed for low- compared to high-frequency words. Experimental results from eye tracking during reading show that participants fixate longer on low- than high-frequency words (for a review, see Rayner, 1998, 2009) and considering that attention leads the eyes, these findings are in line with later orienting of attention for low- than high-frequency words.

We probed readers' attentional profile at five time points during the first fixations on target words to pinpoint the engagement and orienting phases of attention. The probe occurred at the gaze location (central probes) or 6 characters to the left (left probes) or right (right probes) of the gaze location when the eyes fixated on a target word in the line of text for the first time[3]. The accuracy of probe discrimination was the

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[3] In a pilot experiment with 5 participants in which (i) the same stimulus set was used but (ii) participants' only task was to read (there was no probe), the average saccade lengths from the first fixation on target words was 7.6 char. Therefore, a +7 probe would have been a good choice for a right probe because it would have coincided with the average location of the next fixation. However, we initially wanted to assess the effects of word boundaries on attention and, therefore, to have some right probes falling on target words (rather than in the next word). We increased the chances of a right probe occurring on the fixated word by choosing a +6 rather than a +7 probe. Given that (i) readers prefer to fixate somewhere between the middle and the beginning of words (Vitu, O'Regan, & Mittau, 1990) and (ii) the average word length was 6.17 characters (standard deviation = 1.20) for low-frequency words and

measure of attention: better performance on the probe meant more attention at the probe location.

During the engagement phase, visual information from newly fixated words is being encoded and is necessary for reading (e.g., Castelhano & Liversedge, 2011; Rayner et al., 1981, 2003, 2006). During this phase, the probe is encoded at the same time as the word. Encoding of the probe has to compete with encoding of the word and the nature of this competition will be different for central and peripheral probes given that central probes occupy the same spatial location as the encoded word whereas peripheral probes generally do not. Therefore, we did not analyse central probes for the engagement phase. This was not necessary for the analyses of the orienting phase given that during this phase there is no encoding conflict. Hence, orienting of attention towards the right of the gaze location was indexed by comparing performance on probes that occur on the right with probes that occurred elsewhere (at gaze location or on the left).

We now sharpen our predictions for both engagement and orienting phases in terms of attention (as measured by the accuracy of probe discrimination). From the results of Blanchard et al. (1984), we inferred that the orienting of attention has started 120 ms into the fixation. Thus, for the engagement phase, we chose temporal offsets that were smaller than 120 ms. Given that the availability of visual information for subsequent processing is necessary during the first 60 ms or so of the fixation (e.g., Rayner et al., 2003), we examined peripheral probe discrimination (i.e., discrimination of left or right probes) around this period (at 40 ms and 90 ms) and about halfway through a fixation (at 110 ms), expecting that processing of the newly fixated words should focus attention and impair discrimination of peripheral probes but more when the fixated word was low rather than high in frequency. Therefore, we expected to see an effect of frequency on probe discrimination accuracy. We did not expect an effect of spatial offset of the probe or an interaction between temporal and spatial offsets because we expected that attention would be symmetric around the gaze during the engagement phase.

6.24 characters (standard deviation = 1.46) for high-frequency words, probes occurring 7 characters to the right of fixation would almost always fall on the next word; by choosing a +6 probe, 30.6 % of right probes in Experiment 1 fell on the fixated word (15.3 % of low-frequency and 15.2 % of high-frequency words were 8, 9 or 10 char long).

During the orienting phase, on the other hand, we expected that attention would be asymmetric around the gaze. Given that Fischer (1999) found this asymmetry for a temporal offset of 170 ms for a reading-like search task, we chose the temporal offset of 180 ms as the latest temporal offset in Experiment 1. Temporal offsets of 110 ms and 130 ms were chosen as intermediate offsets. Given that attention orients (i) towards the next saccadic target and (ii) away from the already attended locations, we expected that over time attention would (i) increase on the right of the gaze and (ii) decrease elsewhere. In addition, we expected that such increase and/or decrease of attention should occur earlier when the fixated word's frequency was higher. Hence, we expected an interaction between spatial and temporal offset of the probe and word frequency.

We now sharpen our predictions in terms of the effects of the probe on the duration of first fixations on target words and the length of forward saccades from these fixations. The probe was expected to prolong fixations (e.g., Findlay & Walker, 1999; Fischer; 1999; Walker et al., 1997), especially when it occurred halfway through a fixation. This is because, halfway into a fixation, the programming of the upcoming saccade is more likely to be in its labile stage (Becker & Jürgens, 1979) and thus is more prone to change. Thus, we expected an effect of the temporal offset of the probe on the duration of first fixations on target words and on the length of saccades from these fixations, during both engagement and orienting phases.

In Fischer's (1999) study, fixation durations were prolonged more for probes occurring on the left than the right of the gaze location. Compatible with this, Reingold and Stampe (2000, 2004) showed that when the size of the abrupt-onset display changes was small, the increase in fixation durations was smaller for changes that occurred in the direction of the saccade. Thus, we expected that left probes (with spatial offsets of - 6 characters) would prolong the fixations more than right probes (with spatial offsets of + 6 characters). Given that right probes occurred closer to the intended saccadic target than left or central probes, we expected that right probes would attract the eyes more. Given that the intended saccade length in the absence of the probe was bigger than 6 characters (see footnote 3), we expected that a right probe would shorten the upcoming saccade. Thus, we expected that for right probes, compared to left or central probes, (i) saccades should be shortened more, (ii) fixations would be prolonged less and (iii) the effect of the temporal offset of the probe on saccade programming would be weaker. In other words, for both fixation durations and saccade lengths, we expected (i) an effect of the spatial offset of the probe and (ii) an interaction between the spatial and temporal offsets of the probe during both engagement and orienting phases.

The probe, as an abrupt-onset stimulus, was expected to affect the programming of the next saccade (e.g., Fischer, 1999). Nevertheless, if processing of the words at lexical levels was not interrupted by the probe, then an effect of frequency on the timing of saccades should be preserved. In other words, if reading occurred, we expected to see an effect of the frequency of target words on the duration of first fixations on them. This is because an effect of frequency is revealed only if reading occurs (Rayner & Raney, 1996).

2.2 Method

2.2.1 Participants

Participants, aged between 18 and 30 years, were monolingual native British-English speakers with normal or corrected-to-normal vision. All received course credits or money for their participation. Twenty-six participants took part in the experiment. All participants in this study (Experiments 1 to 5) were naïve as to the purpose of the study and had not participated in any study on eye movements in reading before. For each experiment, we recruited new participants.

2.2.2 Apparatus

An EyeLink II head-mounted eye-tracker recorded eye position at 500 Hz while participants read from a 21″ Dell P1330 CRT with 75 Hz refresh, visible display area of 39 cm × 28.5 cm, and resolution of 800×600 pixels. A chin rest controlled head movement and viewing distance (50 cm). Viewing was mono-ocular. The dominant eye was recorded. The non-dominant eye was occluded and could not see the screen but was free to move. Eye dominance was determined using the majority opinion of three tests: the Miles, the Porta, and the Camera test (Roth, Lora, & Heilman, 2002). Participants used the left and right index finger buttons of a sagittally centred Microsoft Sidewinder game-pad to respond to left-oriented and right-oriented probes, respectively.

2.2.3 Stimuli

Each sentence was displayed in grey (the luminance of the text was 7.98 cd/m^2) in 15-point monospaced Courier New Regular font, left-justified along the horizontal midline on an otherwise black display. Each character, including its boundary, subtended 0.37° horizontally. Probes were oblique lines whose top end oriented +22.5° or -22.5° from the vertical axis, with a luminance of 14.72 cd/m^2. Peripheral probes were scaled in accordance with the cortical magnification factor (Rovamo, 1979). Probe width and height were 0.25° and 0.57° respectively.

We used 480 sentence frames, each containing a length-controlled [4] and frequency-manipulated target word [5], yielding meaningful sentence pairs such as:

(a) `There was an accident in the aging` *`church`* `when the walls gave way.`

(b) `There was an accident in the aging` *`trench`* `when the walls gave way.`

The target word ‘church’ (italicised here for illustration purposes) is of high frequency in sentence (a) and of low frequency in sentence (b). All sentence frames were identical until the target words, but 17 differed slightly after the target words to ensure meaningful sentence completions. The target word in each sentence frame was always low-predictable. Items’ contents were not related to each other.

2.2.4 Design

High- and low-frequency conditions were randomly assigned to participants and probe conditions, that is, probe orientation (67.5° or 113.5°), temporal offset (40, 90, 110, 130 and 180 ms) and spatial offset (0 characters or 6 characters to right/left). Counterbalancing yielded 60 lists, each with 480 items per list[6]. Twenty-six lists were

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[4] Target words were between 4 and 10 characters long. The average length was 6.12 (*SD* = 1.14) characters for high-frequency and 6.12 (*SD* = 1.13) characters for low-frequency words.

[5] 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. They were measured on raw word forms rather than lemmas, and were normalized to words per million. According to the BNC counts, high-frequency words had an average (token) frequency of 102.1, and low-frequency words an average (token) frequency of 4.2 per million. The maximum frequency of the low-frequency items was 15.4, and the minimum frequency of the high-frequency items was 23.8 per million.

[6] Of the 480 sentences we used, 246 came from previous research containing sentences with manipulated frequency and controlled predictability (in particular, Drieghe, Desmet & Brysbaert, 2007, Frisson et al., 2005, Hand, O'Donnell & Sereno, 2010). We thank these authors for making their materials available. An additional 234 sentences were devised and tested in a word completion study with 20 different native English-speaking participants to ensure a predictability of less than 0.05. In this control

presented to participants. Stimulus lists were randomly chosen and the remaining lists were not used. Each participant was presented with a different list and was presented with each probe condition 16 times (8 sentences with different high-frequency and 8 sentences with different low-frequency target words).

2.2.5 Procedure

Participants completed three 30-minute sessions, usually on three consecutive days. At the start of each session, a 9-point calibration was performed, and additional calibrations were performed as required. Eye-dominance and dyslexia tests were performed at the start of the first session. Each session started with a practice block of 15 trials (with an additional 30 practice trials in the first session). Each trial started with drift correction relative to a fixation point 3 characters to the left of a line. Figure 2.1 illustrates one trial.

Participants read unrelated single sentences silently in a darkened room. While reading each sentence, a gaze-contingent probe occurred after the first fixation on the target word. This involved an abrupt-onset probe appearing for 30 ms over one character of the text, with the manipulated temporal and spatial offset from the current fixation. Participants continued reading and responded to the probe only after they had finished reading the sentence. When participants' fixations passed an invisible boundary located close to the end of the current sentence, the sentence disappeared from the screen (after a 400 ms delay to impose smooth line transitions). Given that the line of text disappeared as soon as it had been read for the first time, participants should have prioritized reading (as opposed to looking for the probe) during the first pass of reading each line of text. After all, they were unable to take a second look at the line. Thus, the line of text disappeared after the first pass to encourage reading.This was

experiment, each sentence was shown up to the point of (but excluding) the target word, and participants completed the most likely next word. Some of the sentences from the existing literature were modified to fit on our 77-character display. In some cases, it was necessary to change the target word, either due to (i) shortening the sentence, (ii) a change from American to British English, or (iii) the need to control for overall frequency rather than transitional frequency. As all the studies from which items were drawn always listed a predictable word, it was possible to maintain low(er) predictability by ensuring that the replaced word was not the same as (or a close synonym of) the predictable word. Here, I declare that all the credits in terms of making this stimulus set goes to Dr Amit Dubey.

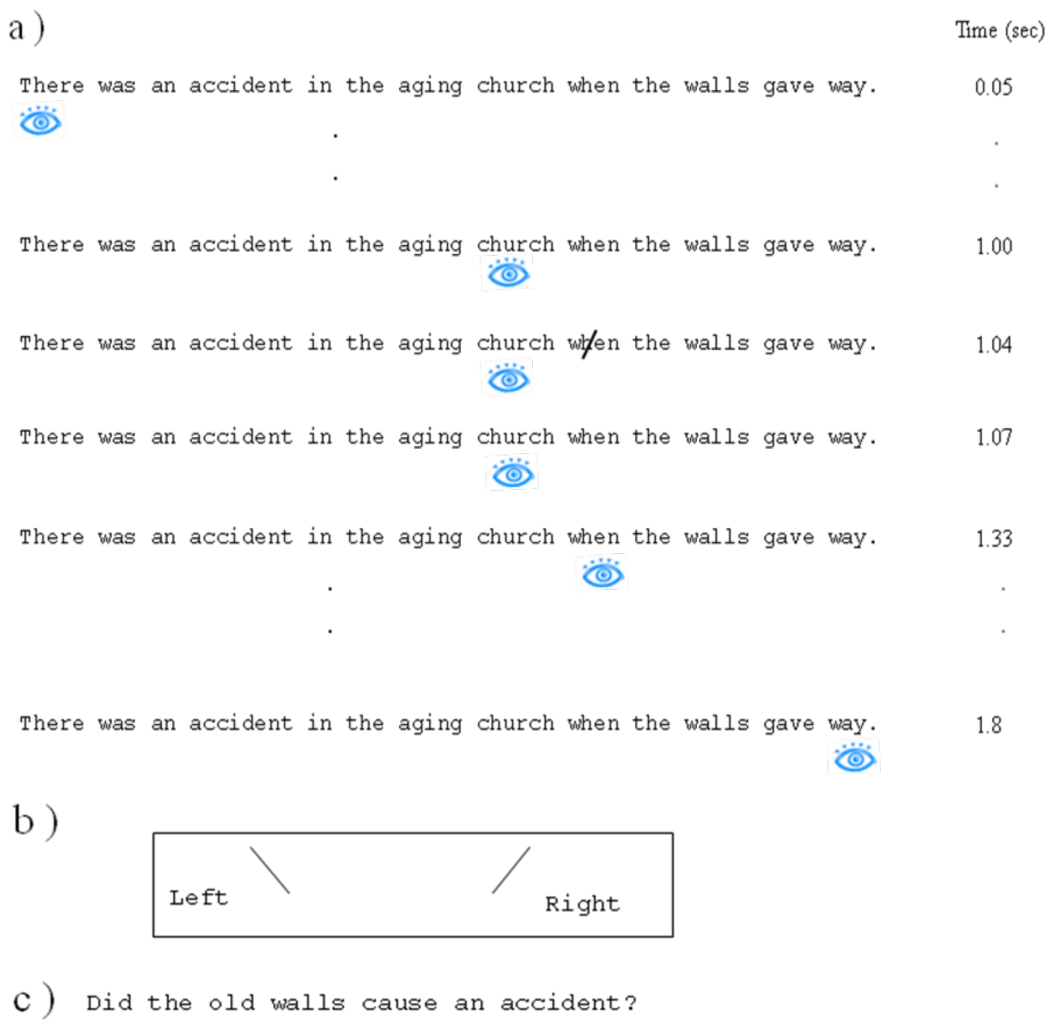

Figure 2.1. A schematic representation of one trial in Experiment 1. One sentence at a time was presented on the screen (a). Participants read the sentence in silence. There was a target word (Wn; here, the word ‘church’) in each sentence. The frequency of the target word was either high or low; here the frequency of ‘church’ is high. When participants’ eyes crossed an invisible boundary to the left of the target word, after some temporal offset from the beginning of the first fixation on the word (here a temporal offset of 40 ms), the probe occurred, here with a spatial offset of +6 characters. The probe was only presented for 30 ms. Participants were instructed to (i) try not to be distracted by the probe and (ii) continue reading. After they read the sentence, another screen appeared and asked them about the orientation of the probe (b). After the response to the probe was made, in 25 % of the trials, another screen appeared asking participants to verbally answer (‘yes’ or ‘no’) to a comprehension question on the sentence they had just read (c).  : gaze location.

followed by another screen, prompting participants to signal the orientation of the probe by selecting the appropriate response button. Finally, for a randomly selected 25% of all sentences, participants answered comprehension questions and received feedback on their verbal responses. All participants answered fewer than 10 out of 120 comprehension questions incorrectly, indicating good text comprehension.

2.3 Results

Twenty-six participants performed the task. Trials were analysed if they satisfied the following filtering criteria: (i) the target word (here, Wn) was fixated; (ii) probe-onset occurred before the termination of the first fixation on Wn; (iii) the first fixation on Wn endured for at least 100 ms and (iv) was followed by a forward[7] saccade; (v) the probe did not occur on a blank space. Moreover, participants with two or more sessions generating < 60 % accuracy in probe discrimination were excluded. As a result, data from twenty-two participants were included in the analysis.

2.3.1 The engagement phase

From a total of 4101 trials, 2670 trials (65.1%) met the filtering criteria. For each dependent variable (error rate, first fixation durations and saccade lengths), a three-way repeated-measures ANOVA evaluated effects of spatial offset (-6 or +6 characters), temporal offset (40, 90 or 110 ms), and word frequency (low and high). The average number of trials per condition per participant was 9.8 (*SEM* = 0.1) samples.

The focus of attention was assessed by analysing probe-discrimination performance as a function of word frequency with left and right probes occurring 40 ms, 90 ms, and 110 ms following the onset of the first fixation on target words.

2.3.1.1 Error rates

Figure 2.2 shows the results of performance on the probe during the engagement phase. A 2 (spatial offset: -6 and +6 characters) X 3 (temporal offset: 40 ms, 90 ms and 110 ms) X 2 (frequency: low and high) repeated-measures ANOVA showed a

[7] By which we mean the saccade was made towards the right of the gaze location but not necessarily to the next word.

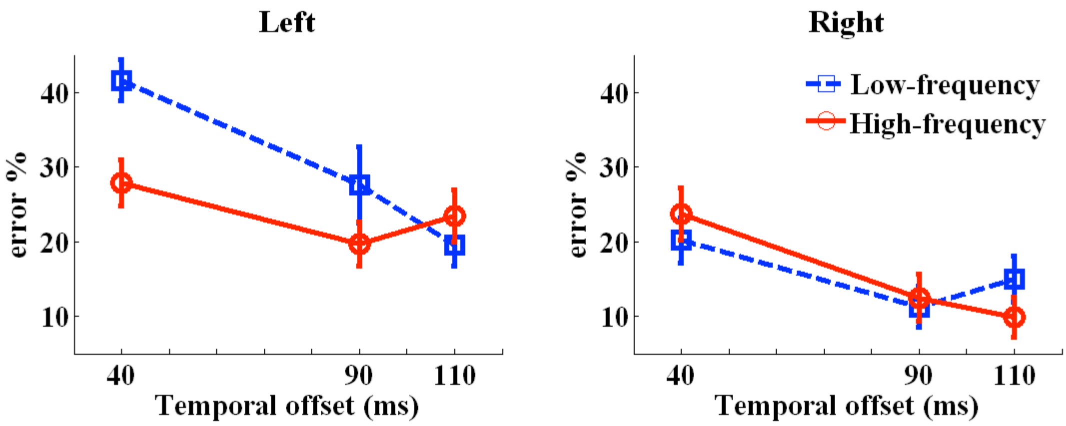

Figure 2.2. Error rates during the engagement phase in Experiment 1. Error rates on probe discrimination as a function of temporal offset of the probe during the engagement phase. Performance is broken down for low-frequency (dashed blue line) and high-frequency (solid red line) words. Error bars show one standard error of the mean. Data for left probes is shown in the left panel and data for right probes is shown in the right panel.

significant effect of spatial offset ($F(1,21) = 13.50$, $p = 0.001$, $\eta^2 = 0.12$) indicated worse performance for left (26.7%; *SEM* = 1.8) than right probes (15.4 %; *SEM* = 2.2). Thus, attention was asymmetric on the gaze during the engagement phase. There was an effect of temporal offset ($F(2, 42) = 20.61$, $p = 0.001$, $\eta^2 = 0.10$). Pairwise comparison with Bonferroni correction showed worse discrimination for temporal offset of 40 ms (28.4 %; *SEM* = 1.8) than both 90 ms (17.8 %; *SEM* = 1.7) and 110 ms (17.0 %; *SEM* = 1.7). Thus, the amplitude of attention increased over time 6 characters from the gaze location. There was no effect of word frequency ($p = 0.17$). There was a three-way interaction between spatial and temporal offset and word frequency ($F(2,42) = 5.33$, $p = 0.008$, $\eta^2 = 0.03$). A separate analysis showed no interaction between word frequency and temporal offset for right probes. For left probes, on the other hand, this interaction was significant ($F(2,42) = 4.06$, $p = 0.024$, $\eta^2 = 0.06$): there was an effect of frequency on the erroneous performance on left probes; this effect decreased over time from temporal offset of 40 ms to 110 ms. We calculated individual best linear fits of error rates across temporal offsets, separately for high- and low-frequency words. The effect of word frequency on the average slope was reliable ($F(1,21) = 10.27$, $p = 0.004$, $\eta^2 = 0.33$). Thus, on the left side of the gaze, as the amplitude of attention increased over time the effect of frequency on the amplitude decreased.

2.3.1.2 First fixation durations on target words

Average durations of the first fixations on high- and low-frequency target words (Wn) are shown separately for different levels of spatial and temporal offsets of the probe in Table 2.1. A 2 (spatial offset: -6 and +6 characters) X 3 (temporal offset: 40 ms, 90 ms and 110 ms) X 2 (frequency: low and high) repeated-measures ANOVA showed an effect of frequency ($F(1,21) = 20.67$, $p = 0.001$, $\eta^2 = 0.05$): the average fixation duration was 312 ms (*SEM* = 12) and 332 ms (*SEM* = 50) on high- and low-frequency words, respectively. Therefore, processing of the words at lexical levels was not disrupted by the probe and reading occurred.

There was an effect of spatial offset ($F(1,21) = 23.50$, $p = 0.001$, $\eta^2 = 0.23$). The average fixation duration was 332 ms (*SEM* = 14) when probes occurred on the left and 312 ms (*SEM* = 12) when they occurred on the right side of fixation. Therefore, probes that occurred on the left prolonged the fixation more compared to probes that occurred on the right. There was an effect of temporal offset ($F(2,42) = 3.9$, $p = 0.026$, $\eta^2 = 0.02$). Average fixation durations for 40, 90, and 110 ms temporal probe offsets were 314 ms (*SEM* = 14), 322 ms (*SEM* = 13), and 329 ms (*SEM* = 13), respectively. Thus, probes that occurred closer to the half way into the fixation prolonged the fixation more compared to those that occurred earlier in a fixation. The interaction between spatial and temporal offsets was not significant ($F(2,42) = 1.79$, $p = 0.17$). However, since our a-priori hypothesis was that effect of temporal offset should be stronger for left than right probes, we ran a 2 (frequency: low and high) X 3 (temporal offset: 40 ms, 90 ms and 110 ms) repeated-measures ANOVA on the duration of first fixation on target words for left and right probes. For left probes, there was an effect of temporal offset ($F(2,42) = 3.65$, $p = 0.034$): the average fixation duration was 332 ms (*SEM* = 15), 346 ms (*SEM* = 17) and 355 ms (*SEM* = 16), for temporal offsets of 40 ms, 90 ms and 110 ms, respectively. Pairwise comparison with Bonferroni correction showed a marginal difference between temporal offsets of 40 ms and 110 ms ($p = 0.060$). For right probes, on the other hand, the effect of temporal offset was not significant ($p = 0.339$). There were no other reliable effects or interactions (all p-values > 0.05).

Average FFD on target words, Wn, (ms)								
Spatial offset (characters)		**-6 (left)**			**+6 (right)**		
Temporal offset(ms)		**40**	**90**	**110**	**40**	**90**	**110**
Wn frequency	**Low**	339	360	370	306	302	310
		17	*21*	*21*	*14*	*12*	*14*
	High	323	330	340	284	295	296
		16	*15*	*15*	*14*	*13*	*12*

Table 2.1. FFD on target words during the engagement phase in Experiment 1. Average first fixation durations (FFD) on target words during the engagement phase, shown for left and right probes with temporal offsets of 40 ms, 90 ms or 110 ms. Mean fixation durations are shown for high- and low-frequency words. Standard errors of the means (SEM) are shown in italics.

2.3.1.3 Saccade lengths

Average saccade lengths from the first fixation on target words (Wn) are shown in Table 2.2. A 2 (spatial offset: -6 and +6 characters) X 3 (temporal offset: 40 ms, 90 ms and 110 ms) X 2 (frequency: low and high) repeated-measures ANOVA showed an effect of spatial offset ($F(1,21) = 18.71$, $p = 0.001$, $\eta^2 = 0.19$, power=0.98). Average saccade length from the first fixation on target words was 7.4 (*SEM* = 0.29) characters for left and 6.5 (*SEM* = 0.28) characters for right probes. As we expected, saccade lengths were shorter for right compared to left probes. There was a marginal interaction between spatial offset and frequency ($p = 0.06$) but the statistical power was low (0.46). For left probes, the average saccade length was 7.43 (*SEM* = 0.29) and 7.32 (*SEM* = 0.31) characters for low- and high-frequency words, respectively. For right probes, the average saccade length was 6.40 (*SEM* = 0.29) and 6.68 (*SEM* = 0.28) for low- and high-frequency words, respectively. There was no other reliable effects or interactions ($p > 0.05$).

Average SL (characters)								
Spatial offset (characters)		**-6 (left)**			**+6 (right)**		
Temporal offset(ms)		**40**	**90**	**110**	**40**	**90**	**110**
Wn frequency	**Low**	7.43	7.35	7.51	6.22	6.60	6.39
		0.29	*0.38*	*0.38*	*0.29*	*0.33*	*0.35*
	High	7.22	7.41	7.35	6.53	6.64	6.80
		0.30	*0.40*	*0.27*	*0.29*	*0.28*	*0.36*

Table 2.2. SL during the engagement phase in Experiment 1. Average saccade lengths (SL) from the first fixation on target words (here, Wn) during the engagement phase, shown for left and right probes with temporal offsets of 40 ms, 90 ms or 110 ms. Mean saccade lengths are shown for high- and low-frequency words. Standard errors of the means (SEM) are shown in italics.

2.3.2 The orienting phase

From a total of 6252 trials, 3802 trials (60.8%) met the filtering criteria. For each dependent variable, repeated-measures ANOVAs evaluated effects of spatial offset (-6, 0 or +6 characters), temporal offset (110, 130 or 180 ms), and word frequency (high or low). The average number of accepted trials per condition per participant was 8.5 (*SEM* = 0.35) samples[8].

Attentional orienting was assessed by analysing probe-discrimination performance as a function of word frequency with left and right peripheral probes *and* central probes occurring 110 ms, 130 ms, or 180 ms into the fixation. We expected that late in a fixation attention should orient (i) towards the right and (ii) earlier and/or stronger where the fixated word is high than low in frequency. Therefore, we expected to see a three-way interaction between word frequency and spatial and temporal offsets of the probe.

[8] From 1232 trials in which the probe occurred with a spatial offset of +6, in 377 (30.6 %) trials it occurred on the target word rather than the next word. A paired-samples *t*-test was run to evaluate whether there was an effect of word boundary for right probes. Given that there was not ($p = 0.30$), the +6 data were pooled from across trials on which the probe occurred on the next word and on the target word.

In terms of fixation durations, similar to our predictions for the engagement phase, we expected to see an effect of frequency on first fixation durations to ensure that reading occurred. In addition, we expected an effect of spatial and temporal offsets on fixation durations and saccade lengths.

2.3.2.1 Error Rates

Figure 2.3 shows probe discrimination error rates for different levels of spatial and temporal offsets and word frequency, during the orienting phase. A 3 (spatial offset: -6, 0 and +6 characters) X 3 (temporal offset: 110 ms, 130 ms and 180 ms) X 2 (frequency: low and high) repeated-measures ANOVA showed a significant effect of spatial offset ($F(2,42) = 14.00$, $p = 0.001$, $\eta^2 = 0.13$), with 20.4% (*SEM* = 2.1), 26.4% (*SEM* = 2.3), and 13.5% (*SEM* = 2.0) errors for left, central, and right probes, respectively. Pairwise comparison with Bonferroni correction showed more accurate performance on right probes compared with left ($p = 0.027$) and central ($p = 0.001$) probes. Thus, attention was asymmetric on the gaze during the orienting phase. There was an interaction between word frequency and spatial offset ($F(2,42) = 5.65$, $p = 0.006$, $\eta^2 = 0.02$). Given that pairwise comparison showed no difference between central and left probes, we broke down this interaction for ‘left and central’ vs. right probes. There was no effect of frequency for left and central probes, $p > 0.05$. For right probes, a 2 (word frequency) X 3 (temporal offset) repeated-measures ANOVA showed an effect of word frequency ($F(1,21) = 10.90$, $p = 0.003$, $\eta^2 = 0.08$). Average error rates were 10.5% (*SEM* = 2.1) for high- and 16.6% (*SEM* = 2.3) for low-frequency words[9]. We did not get the expected three-way interaction ($p > 0.05$). Nevertheless, as we expected there was more attention on the right when the fixated word was a high-frequency than a low-frequency word.

[9] In a separate analysis, we excluded all trials in which a + 6 probe occurred on the target word. A 2 (frequency: low and high) X 3 (spatial offset: -6, 0 and +6 characters) X 3 (temporal offset: 110 ms, 130 ms and 180 ms) repeated-measures ANOVA again showed an interaction between word frequency and spatial offset of the probe: ($F(2,42) = 3.37$, $p = .04$, $\eta^2 = 0.012$). Breaking down this interaction for different spatial offsets, there was a marginal effect of word frequency for right probes ($p = 0.07$) but not for central or left probes.

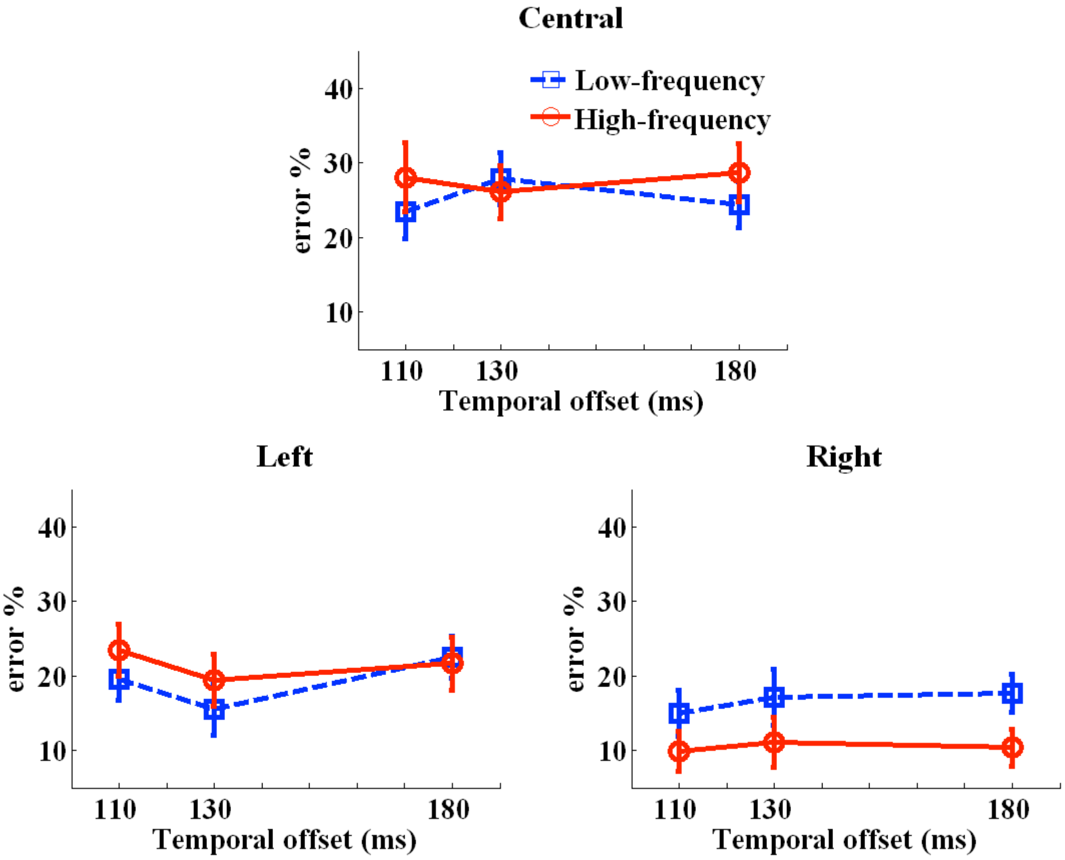

Figure 2.3. Error rates during the orienting phase in Experiment 1. Error rates on probe discrimination as a function of temporal offset of the probe during the orienting phase. Performance is broken down for low-frequency (dashed blue line) and high-frequency (solid red line) words. Error bars show one standard error of the mean. Data for central probes is shown in the top panel. Data for left probes is shown in the bottom-left panel and data for right probes is shown in the bottom-right panel.

2.3.2.2 First fixation durations on target words (Wn)

Average durations of first fixation on target words are shown in Table 2.3. A 3 (spatial offset: -6, 0 and +6 characters) X 3 (temporal offset: 110 ms, 130 ms and 180 ms) X 2 (frequency: low and high) repeated-measures ANOVA showed an effect of word frequency ($F(1,21) = 27.91$, $p = 0.001$, $\eta^2 = 0.04$), confirming that reading occurred. Average fixation duration on high- and low frequency words was 329 ms (*SEM* = 13) and 348 ms (*SEM* = 14), respectively. There was an effect of spatial offset ($F(2,42) = 23.38$, $p = 0.001$, $\eta^2 = 0.21$). Average first fixation durations for left, central, and right probes were 348 ms (*SEM*=14), 359 ms (*SEM* = 17), and 308 ms (*SEM* = 11), respectively. Pairwise comparison with Bonferroni correction showed significant differences between left and right probes ($p = 0.001$) and between central and right probes ($p = 0.001$). As was expected, right probes, compared to left and central probes, prolonged the fixation less. There was an interaction between spatial and temporal offset of the probe ($F(4,84) = 2.71$, $p = 0.035$, $\eta^2 = 0.01$). Given that pairwise comparison with Bonferroni correction showed no difference between left and central probes but showed difference between right and 'left and central' probes, we broke down this interaction for right probes and 'left and central probes'. Analysing only right probes showed no effect of temporal offset on fixation duration ($p = 0.112$). For left and central probes, we conducted a 2 (spatial offset) X 3 (temporal offset) X 2 (word frequency) ANOVA on fixation durations. There was an effect of temporal offset ($F(2,42) = 3.46$, $p = 0.041$, $\eta^2 = 0.03$). An a-priori within-subject contrast showed a marginal difference ($p = 0.07$) between the average fixation duration for the temporal offset of 180 ms (mean = 345 ms, *SEM* = 14) and the mean of fixation durations for temporal offsets of 110 ms and 130 ms (mean = 358 ms, *SEM* = 16). Thus, only for left and central probes fixations were longer for temporal offsets of 110 ms and 130 ms than temporal offsets of 180 ms. There was no other reliable effects or interactions ($p > 0.05$).

2.3.2.3 Saccade lengths

Average saccade lengths from the first fixation on target words are shown in Table 2.4. A 3 (spatial offset: -6, 0 and +6 characters) X 3 (temporal offset: 110 ms, 130 ms and 180 ms) X 2 (frequency: low and high) repeated-measures ANOVA showed an effect of spatial offset ($F(2,42) = 8.31$, $p = 0.001$, $\eta^2 = 0.09$). Average saccade lengths from first fixation on target words was 7.34 (*SEM* = 0.35) , 7.36 (*SEM* = 0.27) and 6.67 (*SEM* = 0.28) for left, central and right probes respectively. Pair-wise comparison with Bonferroni correction showed that right probes were significantly different from left (p = 0.023) and central (p = 0.001) probes. Therefore, as we expected, right probes, compared to the left and central probes, shortened the next saccade. There was an interaction between spatial offset and word frequency ($F(2,42) = 6.08$, $p = 0.005$, η^2 = 0.03). Given that we found no difference between left and central probes, we broke down this interaction for "left and central" and for "right" probes. For "left and central" probes a 2 (spatial offset: -6 and 0 characters) X 2 (frequency: low and high) X 3 (temporal offset: 110 ms, 130 ms and 180 ms) repeated-measures ANOVA showed no effect of frequency ($p > 0.05$). On the other hand, for right probes, there was an effect of word frequency ($F(1,21) = 15.21$, $p = 0.001$, $\eta^2 = 0.12$): Average saccade length was 6.33 (*SEM* = 0.27) and 7.01 (*SEM* = 0.32) for low- and high-frequency words, respectively. There was no other effects or interactions ($p > 0.05$).

Average FFD on target words (Wn) in milliseconds										
Spatial offset (characters)		**-6 (left)**			**0 (center)**			**+6 (right)**		
Temporal offset(ms)		**110**	**130**	**180**	**110**	**130**	**180**	**110**	**130**	**180**
Wn frequency	**Low**	370	355	353	383	374	349	310	316	315
		21	*14*	*16*	*18*	*20*	*16*	*14*	*12*	*12*
	High	340	339	328	357	343	347	296	295	310
		15	*18*	*13*	*20*	*20*	*18*	*12*	*12*	*9*

Table 2.3. FFD on target words during the orienting phase in Experiment 1. Average first fixation durations (FFD) on target words, during the orienting phase, shown for left, central and right probes with temporal offsets of 110, 130 and 180 ms. Mean fixation durations are shown for high- and low-frequency words. Standard errors of the means (SEM) are shown in italics.

Average SL (characters)										
Spatial offset (characters)		-6 (left)			0 (center)			+6 (right)		
Temporal offset(ms)		110	130	180	110	130	180	110	130	180
Wn frequency	**Low**	7.51	7.29	7.39	7.25	7.55	7.58	6.39	6.06	6.54
		0.38	*0.37*	*0.45*	*0.30*	*0.38*	*0.35*	*0.35*	*0.29*	*0.31*
	High	7.35	7.55	6.98	7.14	7.26	7.42	6.80	7.06	7.17
		0.27	*0.44*	*0.19*	*0.28*	*0.30*	*0.29*	*0.36*	*0.30*	*0.47*

Table 2.4. SL during the orienting phase in Experiment 1. Average saccade lengths (FFD) from the first fixations on target words, during the orienting phase, shown for left, central and right probes with temporal offsets of 110, 130 and 180 ms. Mean saccade lengths are shown for high- and low-frequency words. Standard errors of the means (SEM) are shown in italics.

2.4 Discussion

The effect of frequency on the duration of first fixations on target words was preserved. Thus, the probe did not interrupt the processing of the words at lexical levels. In other words, reading occurred and task priority was preserved (see supplementary A).

The accuracy of probe discrimination was the measure of attention. In section 2.4.1, we discuss the results on attention. The probe, as an abrupt-onset stimulus, however, was expected to affect the eyes (e.g., Findlay & Walker, 1999; Fischer, 1999). The results on probe interference with the eyes are discussed in section 2.4.2.

2.4.1 Attention

During the engagement phase of attention, probe-discrimination was better for right than left probes, as early as 40 ms into a fixation. Thus, for the first time, we showed that early in a fixation (i.e., at temporal offsets of 40 ms) attention is asymmetric around the gaze (Ghahghaei, Linnell, Dubey, Fischer & Davis, 2013).

The amplitude of attention, 6 characters from the gaze location on the left or the right, increased over time. We conclude that the focus of attention became wider over time. In other words, attention defocused from 40 ms to 110 ms into a fixation (Ghahghaei et al., 2013).

Defocusing of attention over time is in line with the results of Motter & Simoni's (2008) study. Specifically, in their study, participants were presented with a fixation point followed by a target stimulus at the fixation point, followed again by a conjunction style search array (see Figure 2.4a). Participants were asked to keep the gaze at the central fixation and report the presence/absence of the target stimulus in the array. The search time to detect the presence of the target was the measure of attention. Their results showed that the area around the fixation point within which the target could be detected expanded over time (see Figure 2.4 b-e). However, given that the search times to detect the target was sufficiently long to allow covert shift of attention, the authors acknowledged the possibility of orienting of attention to peripheral locations, rather than the expansion of the focus of attention over time.

The possibility of defocusing of attention, over time, has also been raised by LaBerge, Brown, Carter and Bash (1991). Specifically, in LaBerge et al (1991) study, attention was first focused on a target (T1; digit 7). After a temporal offset, T1

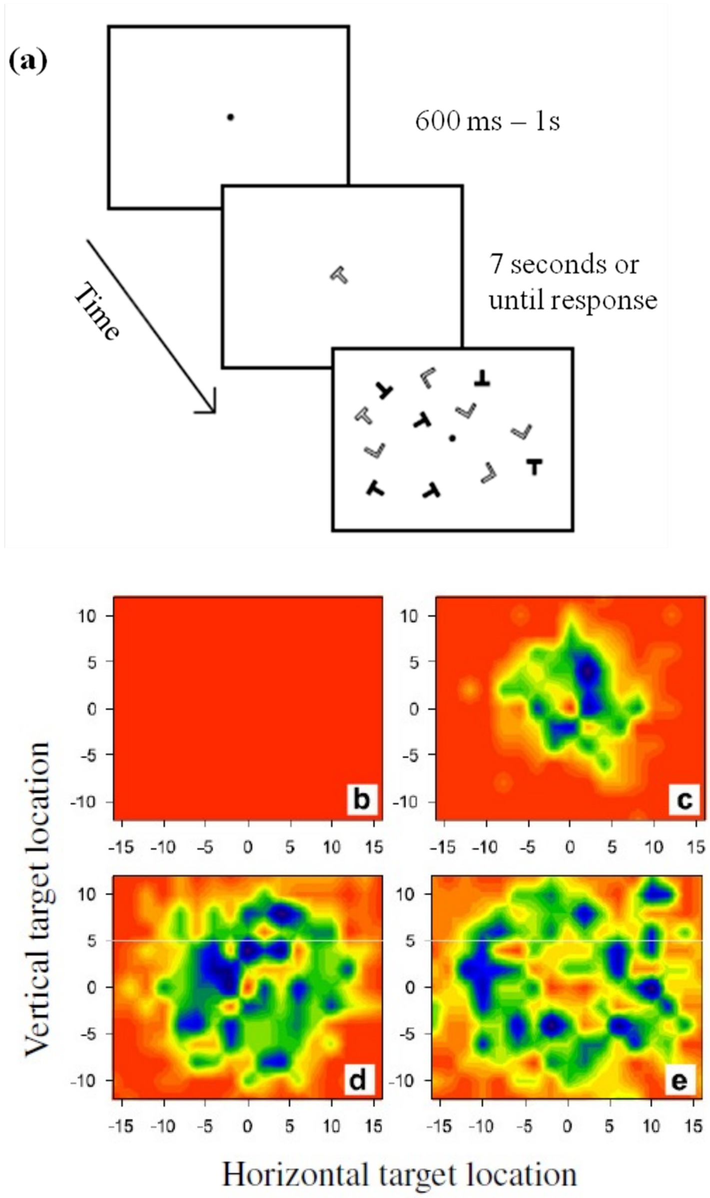

Figure 2.4. Results for Motter and Simoni’s (2008) static viewing condition. (a) A schematic representation of one trial in Motter & Simoni’s (2008) study. (b-e) Contour plots of the locations of targets discovered during sequential 200 ms intervals from the onset of the search array; figures show a summary across 4 subjects. (b) The interval from 200 to 400 ms and shows that no targets were detected in this interval. The spectral color coding range is independently set for each frame from maximum (blue) to minimum (red) counts. The red spot in the center of each frame corresponds to the lack of targets presented at fixation point. Adopted from Figures 1 and 10 in Motter & Simoni (2008). The results are shown for a set size of 24.

disappeared and another target (T2) appeared at the same location of T1. The task was to identify T2 but only if T1 was the digit 7. T2 was embedded in an array of flankers.

The amount of the interference between these flankers with the identification of T2 was the measure of the focus of attention around the location of T2 and, thus, around the location of T1. The idea was that when attention was more focused on T1, attention would be more focused on T2 and this would decrease the interference of flankers with identifying T2. Flankers were with a fixed separation and a change in the amplitude of attention was interpreted as a change in the focus of attention; see Figure 2.5.

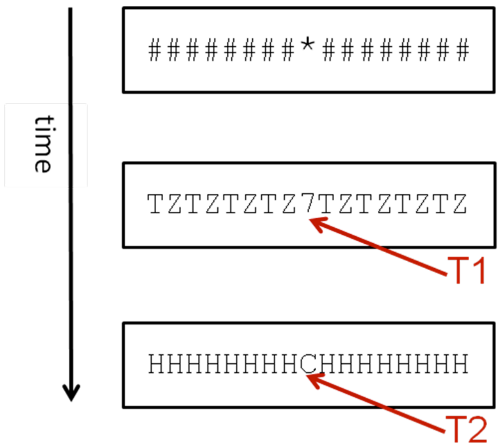

Figure 2.5. A schematic representation of one trial in LaBerge et al.'s (1991) study. Each trial began with a warning signal (########*########) for 1000 ms. Then, two consecutive strings that shared the same spatial location were shown. The temporal offset between the first and the second string ranged from 83 ms to 500 ms. The first string contained a digit target (T1) and the second string contained a letter target (T2). The first string was made of 17 characters of alternating 'Z' or 'T' with either 'Z' or 'T' or '7' in the middle. In the second string, the middle character was a letter from the set of (C, H, S, K); this character was surrounded by eight identical characters on each side from the set of (C, H, S, K, X). Participants were asked to detect whether the letter target (T2) belonged to the set of (C, S) or (H, K) but only if the digit target '7' was presented in the centre of the first string (T1).

LaBerge et al (1991) manipulated the load of the task by manipulating the temporal offset between T1 and T2. They found that the interference of flankers on identifying T2 (i) increased from temporal offset of 83 ms to 350 ms and (ii) saturated at temporal offset of 350 ms. The authors concluded that, with shorter temporal offsets, the load of the processing of T1 was higher resulting in more focused attention. Nevertheless, they also acknowledged that "it is possible that T1 duration does not affect the initial spread of attention, but that initially identical spreads of attention broaden with increasing SOA [temporal offset]" (LaBerge et al, 1991, page 72). This interpretation is in line with a defocusing of attention over time as suggested by our results.

In LaBerge et al.'s (1991) study, the manipulation of the load of the task/stimulus was confounded with the time when attention was measured. In our study, the manipulation of load (i.e., manipulating word frequency) was not confounded with the time at which attention was measured (i.e., the temporal offset of the probe). Our load manipulation affected the focus of attention (Ghahghaei et al., 2013). Performance on the probe discrimination was worse when the fixated word was low rather than high in frequency. Thus, we conclude that attention was focused more on low- than high-frequency words. The effect of frequency on the focus of attention was revealed for left probes that occurred early in a fixation (i.e., temporal offset of 40 ms). Given that the perceptual span is skewed towards the right (McConkie & Rayner, 1975), right probes were sensitive to the effects of frequency less than left probes. Nevertheless, attention defocused around the gaze location on both the left and right sides of the gaze and defocusing was faster when the fixated word was high rather than low in frequency. The effect of frequency on left probes was at its strongest at 40 ms into a fixation and disappeared by 110 ms.

One might argue that the improvement in the performance on the probe, during the first half of a fixation, would be explained by saccadic suppression (Erdmann & Dodge, 1898; Haber & Hershenson, 1973). We note, however, that saccadic suppression should impact the timecourse of any change in performance equally for left and right probes, regardless of the frequency of the fixated word. This was not the case. Thus, in addition to any effects of saccadic suppression, attention affected performance on the probe.

From halfway through a fixation (at temporal offsets of 110 ms), the orienting phase started. There was more attention on the right than the left of gaze location during this phase. Such an asymmetry was expected given that attention leads the eyes. However, we did not get the expected interaction with time. Over time (i.e., over temporal offsets of 110 ms, 130 ms and 180 ms), the accuracy of probe discrimination did not (i) decrease for left or central probes or (ii) increase for right probes. It is possible that these expected changes occur later than 180 ms into a fixation. Although we did not get the expected increase/decrease of attention, over time, we got an effect of frequency on the accuracy of discrimination of right probes: when the fixated word was high rather than low in frequency, there was more attention 6 characters to the right of the gaze location. In other words, attention oriented towards the right more when the fixated word was high rather than low in frequency (Ghahghaei et al., 2013).

2.4.2. Eye-movement behaviours

The probe, as an abrupt-onset stimulus, was expected to affect the upcoming saccade namely, its timing (i.e., fixation duration) and its metrics (e.g., its length). In Fischer's (1999) study, the probe did not occur in some trials in the reading task. These trials provided a baseline for undisturbed fixation durations and saccade lengths. Fischer showed that fixation durations were prolonged and saccade lengths were shortened by the probe.

Here, in Experiment 1, the probe occurred in all trials. Furthermore, we analysed the duration of first fixations rather than single fixations. Thus, in our study, trials in which there was more than one fixation on the target word were included in the analysis. Nevertheless, given that a subset of the stimulus set that we used was from the stimuli that Frisson et al. (2005) and Hand et al. (2010) used, a comparison between their data and our data, on the duration of first fixations on target words, suggested that fixation durations were prolonged by the probe in our study.

Probes occurring on the left of or at the gaze location prolonged fixations more than those occurring on the right of the gaze, especially if they occurred halfway through a fixation, resulting in an interaction between spatial and temporal offsets. Thus, the probe interfered with the *timing* of the upcoming saccade *less* when it occurred (i) closer to the saccadic target (Reingold & Stampe, 2000, 2004) and (ii) outside the labile stage of saccade programming (Becker & Jürgens, 1979).

The *length* of the upcoming saccade[10] was also affected by the probe. Saccades were shorter for right than left and/or central probes. However, there was no effect of or interaction with the temporal offset of the probe. Given that decisions on 'where' and 'when' to make a saccade are made via different pathways in the brain (Van Gisbergen et al., 1981), it is possible that the probe affected the timing (i.e., fixation durations) and the length of the upcoming saccade in different ways.

[10] This was the first forward saccade that was made after the probe occurred. All forward saccades including refixations were included.

We expected an effect of frequency on the timing of the upcoming saccade (i.e., fixation duration), but not necessarily on its length, to confirm that reading occurred. As we expected, there was an effect of frequency on fixation durations. Besides, there was an effect of frequency on saccade lengths for right probes. This frequency effect was marginal during the engagement phase and significant during the orienting phase. A smaller average saccade length from the first fixation on a low- than high-frequency word can be explained by more refixation on low- than high-frequency words (Pollatsek & Rayner, 1990). Fischer (1999) did not report such an effect of frequency on saccade lengths, presumably because he only analysed trials where there was a single fixation on the target word (i.e., no refixation).

The fact that there was an effect of frequency on saccade lengths only for right probes suggests that any effects of frequency on the decision regarding the next saccadic target is so subtle that it can only survive after the probe occurs if (i) the probe occurs close to, or within, the non-labile stage of the saccade programming and (ii) the probe's location is close to the intended saccadic target.

On the other hand, one could argue that we see an effect of frequency on the length of saccades that follow right probe because, for these probes, task priorities were not preserved. In other words, one could argue that the observed effect of frequency on saccade lengths was not an effect of the lexical processing load of the fixated word on saccade programming; rather, for low-frequency words, compared to high-frequency ones, the load of the primary task was harder and task priority was not preserved. If this argument were true, we should not see an effect of frequency on saccade lengths in the absence of the probe. We investigated this in Experiment 2.

2.5. Next experiment

In Experiment 1, we showed that attention was asymmetric around the gaze as early as 40 ms into a fixation. In addition, the amplitude of attention 6 characters to the left of the gaze location was smaller for low- than high-frequency words; we concluded that attention was focused more when the fixated word was low rather than high in frequency. In Experiment 2, we probed attention as early as 10 ms into the fixation (i.e., at the earliest temporal offset that current technology allows) to investigate whether (i) the asymmetry of attention and (ii) the effects of the frequency of the fixated word on the focus of attention occurred from the very beginning of the fixation.

In Experiment 1, by 180 ms into a fixation, we found evidence of the orienting of attention towards the next saccadic target: there was more attention, 6 characters to the right of the gaze location, when the fixated word was high rather than low in frequency. However, over time, there was no evidence of (i) a decrease of attention at the gaze and/or to the left of the gaze or (ii) an increase of attention to the right of fixation. This increase/decrease of attention may occur after 180 ms during a fixation. To investigate this, in Experiment 2, we probed attention even later (i.e. at temporal offsets of 220 ms into a fixation).

In Experiment 1, there was an effect of the frequency of the fixated word on saccade lengths but only when the probe occurred 6 characters to the right side of the gaze. To ensure that this frequency effect was not caused by the probe, we included control trials in Experiment 2 in which the probe did not occur.

Supplementary Information A

A.1 Was task priority preserved?

In our study, we asked participants to prioritize the reading task over the probe discrimination task. If task priority was preserved, then performance on the probe was a direct measure of spatial attention. However, human subjects usually want to perform well on any task they do. This is true also when they perform dual or multiple tasks. In our study, although we emphasised the reading task and only provided feedback for this task, participants probably wanted to perform well on both reading and probe discrimination tasks. Participants presumably had some idea of how well they performed on the probe discrimination task. It is also possible that they had some idea of their overall performance as derived from a weighted sum of their performance on the reading task *and* the discrimination task. Given that instructions were to afford a higher priority to the reading task, the weight of the reading task was presumably larger than the weight of the discrimination task in deriving overall performance. Given that performance on the probe discrimination task should deteriorate as the reading task becomes more difficult, it is possible that when the reading task was harder (e.g., as when reading low- rather than high-frequency words), participants increased the weight of the probe discrimination task to improve overall performance. In the most extreme instance, the weight of the probe discrimination task might become bigger than the reading task, reversing the task priority. In other words, probe discrimination might improve as processing the fixated word becomes more demanding. This being the case, task priority would not be preserved and performance on the probe would not be a measure of spatial attention. This was however not the case. Results from Experiment 1 are re-plotted for peripheral probes in the form of an AOC curve (Sperling and Melchner, 1978) in Figure SA1. In Experiment 1, the effect of frequency on probe discrimination accuracy was observed 40 ms into a fixation (for left probes) and 130 ms and 180 ms into a fixation (for right probes). In both cases, when the target word was low rather than high in frequency, (i) the eyes fixated longer on the target word (i.e., the primary task was harder) *but* (ii) accuracy on the probe was poorer (i.e., performance on the secondary task was worse). Thus, the AOC curve did not show any evidence of a trade-off between the primary (i.e., reading) and the secondary task (i.e., discriminating the probe). Thus, we conclude that task priority was preserved.

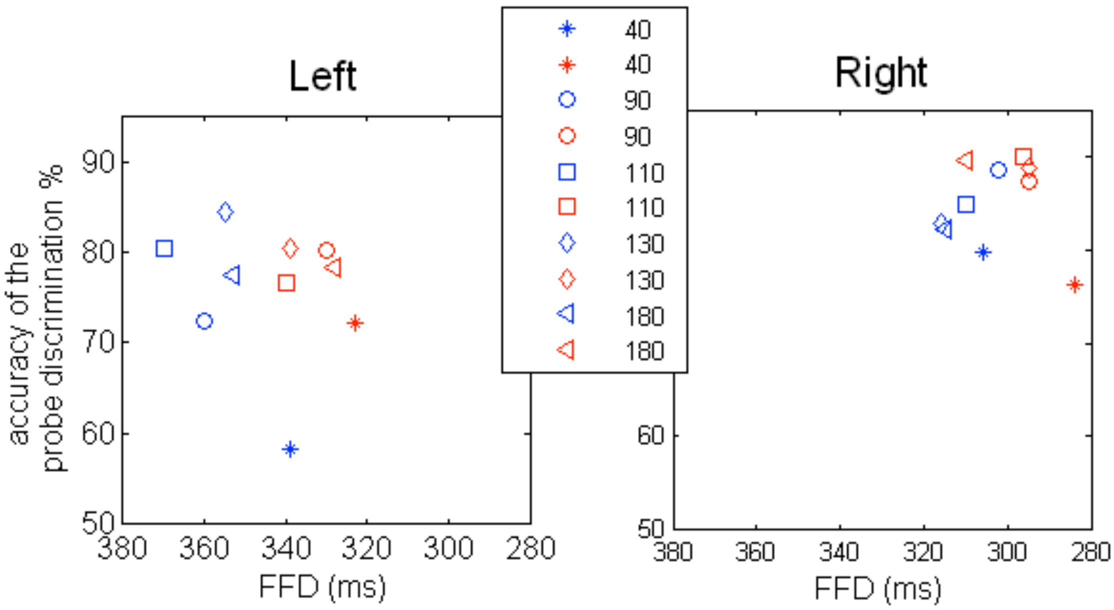

Figure SA1. AOC for peripheral probes in Experiment 1. The figure shows the average accuracy of probe discrimination as a function of the average duration of first fixations on target words. Blue/red marks represent performance for when the fixated word was a low/high-frequency one respectively. Different marks represent different temporal offsets of the probe (see the legend). Note that the x-axis is descending and the y-axis is ascending.

Chapter 3

Further investigation of the dynamics of attention and effects of the probe on eye movements

3.1 Introduction

We assumed two phases for attention over the course of a fixation: the engagement phase that lasts until halfway into the fixation and the orienting phase that starts about halfway into the fixation and lasts until the end of the fixation. In Experiment 1, there was an effect of frequency on attention, during the engagement phase, as early as 40 ms into a fixation. We reasoned that this early effect of frequency was because participants previewed words and so their processing started before they were fixated (e.g., Rayner, 1975a, 1975b). Consequently, 40 ms into the first fixation on a word, its processing was sufficiently advanced to reach those levels that correspond to its frequency. The amplitude of attention, 6 characters from the gaze location, was smaller for low- than high-frequency words. We concluded that attention was more focused on low- than high-frequency words (Ghahghaei et al., 2013). The effect of frequency was only revealed by left probes presumably because attention was allocated more to the right than the left side of the gaze location and, consequently, right probes were less sensitive to the effect of frequency.

In Experiment 2, we investigated whether (i) such an asymmetric profile of attention and (ii) the effect of frequency on the focus of attention exist even earlier in a fixation. Thus, we probed attention very early into the first fixation on target words (at temporal offsets of 10 ms; the earliest time point that current technology allows), 6 characters to the left or right of the gaze location.

During the orienting phase, in Experiment 1, there was an effect of frequency on attention but only for right probes: performance on right probes was better when the fixated word was high rather than low in frequency. This is in line with earlier orienting of attention towards the next saccadic target for high- than low-frequency words. However, there was no sign of this orienting, over time: from 110 ms to 180 ms through a fixation, accuracy of probe discrimination (i) did not decrease for left and central probes and (ii) did not improve for right probe. It is possible that these time effects are only revealed later in a fixation. Therefore, in Experiment 2, we probed attention at even later times (at temporal offsets of 180 ms and 220 ms) at the gaze location and 6 characters to the left or right of the gaze.

The results of Experiment 1 showed that reading occurred and task priorities were preserved: fixation durations were longer on low- than high-frequency words. In Experiment 2, we included trials where no probe occurred, the *control* trials, as a baseline for eye-movement behaviours. We expected that the probe would prolong the duration of fixations (e.g., Fischer, 1999; Rayner, Liversedge, White, & Vergilino-Perez, 2003) but the effect of frequency on fixation durations would be independent of the presence or absence of the probe.

We now sharpen our predictions in terms of attention (measured by the accuracy of probe discrimination). We expected that attention should be asymmetric around the gaze from the very beginning of a fixation. This is because attention remained asymmetric around the gaze for all temporal offsets in Experiment 1. Therefore, we expected to see an effect of spatial offset on probe discrimination. In addition, in Experiment 1, the amplitude of attention increased over time, 6 characters from the gaze location; we concluded that attention defocused over time during the engagement phase. We expected that the defocusing of attention would start from the very beginning of a fixation. This being the case, we expected better performance on peripheral probes occurring 40 ms into a fixation than those occurring 10 ms into a fixation. To investigate this, we compared peripheral probes occurring with a temporal offset of 10 ms (in Experiment 2) with peripheral probes occurring with a temporal offset of 40 ms (in Experiment 1).

For probes occurring 10 ms into a fixation, in Experiment 2, we expected that any effects of frequency on the focus of attention would be revealed by both left and right probes. This is because we expected that attention would be more focused on the gaze 10 ms than 40 ms into the fixation. We thus expected to see an effect of frequency on the focus of attention. Nevertheless, any effects of frequency on the focus of attention should be weaker 10 ms than 40 ms into a fixation. This is because when the word is just fixated, processing of the word is less likely to be sufficiently advanced to reveal an effect of frequency on attention.

During the orienting phase, shortly before the fixation ends and the upcoming saccade is made, saccadic suppression (Haber & Hershenson, 1973) degrades perception for all locations around the gaze including the gaze location. This can lead to worse performance on probes occurring 220 ms into the fixation as opposed to 180 ms. Saccadic suppression degrades performance on left, central and right probes. On the other hand, over time (i.e., from 180 ms to 220 ms into a fixation), orienting of attention towards the right of the gaze location should result a better performance on right probes and a worse performance on central or left probes. Thus, for left and central probes, we expected that performance would be worse for temporal offsets of 220 ms than 180 ms. For right probes, on the other hand, we did not expect a strong effect of temporal offset given that saccadic suppression and orienting of attention should work in opposite directions.

Furthermore, we expected that orienting should occur earlier for high- than low-frequency words. Hence, for high-frequency words, compared to low-frequency ones, performance should be (i) better on right probes and (ii) worse on left and central probes. Thus, an interaction between word frequency and the spatial and temporal offsets of the probe was expected.

We now sharpen our predictions in terms of the effects of the probe on fixation durations and saccade lengths. We expected to see an effect of the frequency of the fixated word on saccade lengths in control trials (i.e., trials without a probe). This is because refixations are more likely on low- than high-frequency words (Pollatsek & Rayner, 1990). An effect of frequency on saccade lengths is expected to be preserved during the orienting phase of attention given that (i) the probe occurred relatively late in a fixation (at temporal offsets of 180 ms and 220 ms) and (ii) presumably close to the non-labile stage of saccade programming (Becker & Jürgens, 1979).

In line with this, we did not expect an effect of temporal offset on saccade lengths, during the orienting phase. In addition, based on the results of Experiment 1, we expected no effect of the temporal offset of the probe (i.e., 10 ms in Experiment 2 and 40 ms in Experiment 1) on saccade lengths during the engagement phase.

Based on the results in Experiment 1, during both engagement and orienting phases, we expected an effect of the spatial offset of the probe on saccade lengths and fixation durations. We expected that probes occurring on the right side of the gaze, compared to those occurring at the gaze location or on the left side, should shorten the saccades more and prolong the fixations less.

During the engagement phase, we expected that probes with a temporal offset of 10 ms (data from Experiment 2) would prolong the fixations less compared to those with a temporal offset of 40 ms (data from Experiment 1); this is because in Experiment 1, fixation durations increased with temporal offset during the engagement phase. Thus, we expected an effect of temporal offset on fixation durations. During the orienting phase on the other hand, we did not expect an effect of the temporal offset of the probe on fixation durations given that probes occurred late in a fixation and presumably during or close to the non-labile stage of saccade programming.

Most importantly, we expected that fixation durations should be longer on low- than high-frequency words, independent of the presence or absence of the probe, during both engagement and orienting phases. An effect of frequency on fixation duration would confirm that reading occurred (Rayner & Raney, 1996).

3.2 Method

3.2.1 Participants

Participants were students from Goldsmiths, University of London, aged between 18 and 30 years, were monolingual native British-English speakers with normal or corrected-to-normal vision. All received course credits for their participation. Twenty-six participated (10 males and 16 females).

3.2.2 Apparatus

The same apparatus as in Experiment 1 was used for Experiment 2.

3.2.3 Stimuli

The same stimulus set that was used in Experiment 1, was also used for Experiment 2.

3.2.4 Design

Design in Experiment 2 was as in Experiment 1 but in the so-called *control trials* (20 % of the whole trials) probes did not occur. Control trials were randomly presented amongst other trials. Participants were informed that in some trials there was no probe, but they did not know which trials. In the remaining trials (80% of the whole trials), as in Experiment 1, the probe occurred either at the gaze location (central probe) or 6 characters to the left (left probes) or to the right (right probes) of the gaze location. The probe occurred early (temporal offset of 10 ms) or late (temporal offset of 180 or 220 ms) in a fixation when the eye landed on the target word (here, Wn). Temporal offset of 10 ms , 180 ms, 220 ms and 500 ms (a dummy temporal offset for which no probe occurred and was only used for control trials) and spatial offset of -6, 0 and +6 characters and probe direction (tilted to left or right) was randomised for low- and high-frequency words. Given that there were 480 items, there was 20 items per condition. The temporal offset of 500 ms was a dummy one and was used for the control trials; given that 3 spatial offsets were used for each temporal offset, there was a total of 20 X 3 = 60 items for each level of word frequency in the control condition.

In Experiment 1, we lost a good portion of trials due to the probes that occurred on a blank space. To avoid this, from Experiment 2 onward, should a probe had occurred on a blank space, the probe was moved one character to the right. So a probe with a spatial offset of +6 characters occurred with spatial offset of +7 characters if +6 happened to be a blank space, and a probe with a spatial offset of -6 characters occurred with spatial offset of -5 if -6 happened to be a blank space. The spatial resolution of EyeLink II is about 0.5 visual degrees, which is bigger than the extent of one character in visual degrees in our experiment. Thus, moving the peripheral probes by 1 character to avoid the loss of trials seemed reasonable.

3.2.5 Procedure

Procedure was the same as in Experiment 1. Participants were informed that there was no probe in some trials but they did not know which trials.

3.3 Results

In Experiment 2, similar to Experiment 1, in each trial, the target word was Wn. That is, probes occurred during the first fixation on target words. Trials were analysed if they satisfied the following filtering criteria: (i) the target word was fixated; (ii) the first fixation on the target word was at least 100 ms and followed by a forward saccade and (ii) probe-onset occurred during this fixation. Moreover, participants with two or more sessions generating < 60% accuracy in probe discrimination were excluded. As a result, data from 22 participants were included in the analysis.

For the control trials, a trial was accepted if (i) the target word was fixated; (ii) the first fixation on the target word was at least 100 ms and followed by a forward saccade.

We first provide the results for the duration of the first fixation on target words and the length of the forward saccades that followed them in the control trials. Then we provide the results on attention for engagement phase and orienting phases. The effects of word frequency and probe status (i.e., presence or absence of the probe) on the duration of first fixations and the length of the following forward saccades was further investigated for the engagement phase and for orienting phases in the corresponding sections.

3.3.1 Control trials: eyes' behaviour in the absence of the probe

The average number of accepted trials per condition per participant was 37.45 (*SEM* = 0.94) samples. The effects of frequency on the duration of first fixations and the length of the forward saccades were investigated by paired-sample *t*-tests.

3.3.1.1 First fixation durations

There was an effect of frequency ($t(21) = 3.689$, $p = 0.001$; *2-tailed*). The average duration of the first fixation on target words was 318 ms (*SEM* = 11) for low-frequency and 295 ms (*SEM* = 10) for high-frequency words.

3.3.1.2 Saccade lengths

There was an effect of frequency ($t(21) = -2.69$, $p = 0.015$; *2-tailed*). The average saccade length was 7.1 characters (*SEM* = 0.25) for low- and 7.6 characters (*SEM* = 0.25) for high-frequency words. Thus, frequency affected both fixation durations and saccade lengths in the absence of the probe.

3.3.2 The engagement phase

From a total number of 1361 trials where peripheral probes occurred with a temporal offset of 10 ms, 1098 (80%) trials met the filtering criteria. A 2 (frequency: low and high) X 2 (spatial offset: - 6 and + 6) repeated-measures ANOVA evaluated effects of spatial offset and word frequency on error rates, the duration of first fixation on target words and saccade lengths from these fixations. The average number of accepted trials per condition per participant was 12.5 (*SEM* = 0.38) samples.

We investigated the effects of the presence/absence of the probe on fixation durations and saccade lengths by running a 2 (frequency: low and high) X 2 (probe status: present and absent) repeated-measures ANOVA on first fixation durations and saccade lengths.

Give that there was no evidence of different task strategies in Experiments 1 and 2 (see supplementary B), for error rates, fixation durations and saccade lengths, we compared the probes occurring with a temporal offset of 10 ms (Experiment 2) with those occurring with a temporal offset of 40 ms (Experiment 1). We did so by conducting a 2 (frequency: low and high) X 2 (spatial offset: - 6 and + 6) X 2 (temporal offset: 10 ms and 40 ms) mixed-effects ANOVA with temporal offset as a between-subject variable on data from Experiment 1 (temporal offset of 40 ms) and Experiment 2 (temporal offset of 10 ms).

3.3.2.1 Error rates in Experiment 2

The average error rates are shown in Figure 3.1. A 2 (frequency: low and high) X 2 (spatial offset: - 6 and + 6) repeated-measures ANOVA showed an effect of spatial offset ($F(1,21) = 17.73$, $p = 0.001$, $\eta^2 = 0.15$). Average error was 43 % (*SEM* = 1.9) for left and 33 % (*SEM* = 2.7) for right probes. Thus, attention was asymmetric around the gaze location even 10 ms through the fixation. The effect of frequency was not significant but was in the expected direction ($p = 0.15$). The average error rate was 41.2 % (*SEM* = 2.9) and 35.6 % (*SEM* = 2.5) for low- and high-frequency words, respectively. There was no interaction ($p = 0.67$).

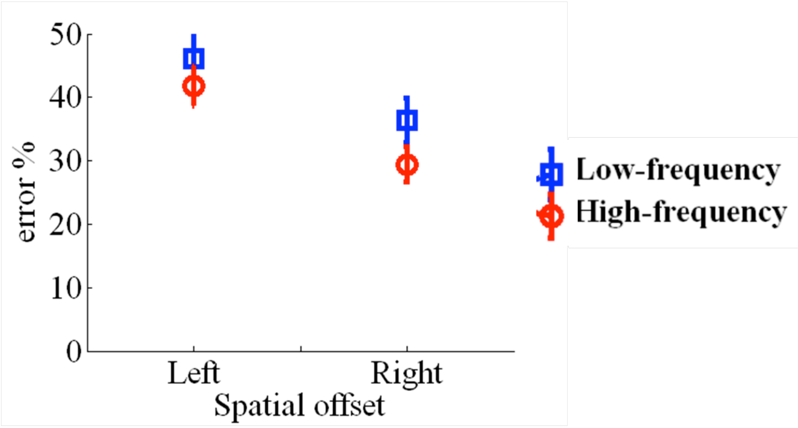

Figure 3.1. Error rates during the engagement phase in Experiment 2. Error rates on probe discrimination as a function of spatial offset of the probe during the engagement phase (temporal offsets of 10 ms). Performance is broken down for low-frequency (blue square) and high-frequency (red circle) words. Error bars show one standard error of the means.

3.3.2.2 Error rates in Experiments 1 and 2, a comparison

We ran a 2 (frequency low and high) X 2 (spatial offset: - 6 and + 6) X 2 (temporal offset: 10 ms, trials from Experiment 2, and 40 ms, trials from Experiment 1) mixed-effects ANOVA with temporal offset as a between-subject variable on error rates.

There was an effect of spatial offset ($F(1,42) = 14.27$, $p = 0.001$, $\eta^2 = 0.09$). The average error rate was 39.3 % (*SEM*= 1.60) and 29.8 % (*SEM* = 2.21) for left and right probes, respectively. More importantly, there was an effect of temporal offset ($F(1,42) = 7.09$, $p = 0.011$). The average error rate was 38.2 % (*SEM* = 2.3) and 30.6 % 9 *SEM* =2.1) for temporal offset of 10 ms and 40 ms, respectively. Therefore, the amplitude of attention increased from 10 ms to 40 ms into a fixation. There was an effect of frequency ($F(1,42) = 4.87$, $p = 0.032$, $\eta^2 = 0.03$): average error rate was 37.4 % (*SEM* = 1.75) and 31.7 % (*SEM* = 2.1) for low- and high-frequency words, respectively. There was no interaction between word frequency and spatial offset ($p = 0.18$) or temporal offset ($p = 0.99$). There was a marginal interaction between spatial and temporal offsets and word frequency ($F(1,42) = 3.35$, $p = 0.074$, statistical power = 0.43). The statistical power was low. Nevertheless, the effect of frequency was only significantly revealed on the left side of the gaze location 40 ms into the fixation (results in Experiment 1).

3.3.2.3 First fixation durations on target words (Wn)

The average durations of the first fixations are shown in Table 3.1. A 2 (frequency: low and high) X 2 (spatial offset : - 6 and + 6) repeated-measures ANOVA showed an effect of word frequency ($F(1,21) = 6.69$, $p = 0.017$, $\eta^2 = 0.07$): the average fixation duration was 334 ms (*SEM* = 11) and 317 ms (*SEM* = 13) for low- and high-frequency words, respectively. An effect of frequency on the duration of the first fixation confirmed that reading occurred.

There was an effect of spatial offset ($F(1,21) = 4.46$, $p = 0.046$, $\eta^2 = 0.09$). The average duration of the first fixations was 336 ms (*SEM* = 12) for left and 315 ms (*SEM* = 12) for right probes; however, the statistical power was low (power = 0.52).

Average FFD on target words (Wn)			
Spatial offset (characters)		**-6 (chars)**	**+6 (chars)**
Temporal offset(ms)		**10**	**10**
Wn frequency	**Low**	344	325
		12	*14*
	High	328	307
		12	*13*

Table 3.1. FFD on target words during the engagement phase in Experiment 2. Average first fixation durations (FFD) on target words (here, Wn), in ms, during the engagement phase, shown for left and right probes, broken down for low- and high-frequency target words. Standard errors of the means are shown in italics.

3.3.2.4 Fixation durations and the effects of the presence/absence of the probe

We investigated the effect of probe status (present or absent) on the duration of first fixation on target words by running a 2 (frequency: low and high) X 2 (probe status: present and absent) repeated-measures ANOVA. The average number of accepted trials per condition per participant was 37.45 (*SEM* = 0.94) samples for the absent condition[11] and 24.78 (*SEM* = 0.77) for the present condition. The effect of word frequency was significant ($F(1,21) = 17.78$, $p = 0.001$, $\eta^2 = 0.20$): the average duration of the first fixation was 326 ms (*SEM* = 11) and 306 ms (*SEM* = 11) for low- and high-frequency words, respectively. There was an effect of probe status ($F(1,21) = 17.17$, $p = 0.001$, $\eta^2 = 0.17$): the average duration of the first fixation was 326 ms (*SEM* = 12) and 306 ms (*SEM* = 10) for present and absent conditions, respectively. There was no interaction ($p = 0.67$). Thus, the probe did not interfere with the effects of frequency on fixation durations.

3.3.2.5 Fixation durations in Experiments 1 and 2, a comparison

We compared the effects of peripheral probes with a temporal offset of 10 ms (in Experiment 2) with those with a temporal offset of 40 ms (in Experiment 1) on first fixation durations. To do so, we ran a 2 (temporal offset: 10 ms and 40 ms) X 2 (spatial offset: -6 and +6) X 2 (frequency: low and high) mixed-design ANOVA on first fixation durations with temporal offset as a between-subject variable. The effects of frequency ($p = 0.002$) and spatial offset ($p = 0.002$) were significant. There was no effect of temporal offset ($p = 0.525$) and no interactions ($p > 0.05$).

3.3.2.6 Saccade lengths

The average saccade lengths from the first fixation on target words are shown in Table 3.2. A 2 (frequency: low and high) X 2 (spatial offset: - 6 and + 6) repeated-measures ANOVA showed an effect of spatial offset ($F(1,21) = 11.38$, $p = 0.002$, $\eta^2 = 0.19$). The average saccade was 7.3 characters (*SEM* = 0.28) for left and 6.7 characters (*SEM* = 0.25) for right probes. There was no effect of frequency and not interaction ($p > 0.50$).

[11] Given that the same sets of ‘probe absent’ data were used to investigate effects of probing in the engagement phase and in the orienting phase, *p*-values should be corrected (multiplied by 2). Here the uncorrected *p*-values are reported.

Average saccade length (characters)			
Spatial offset (characters)		**-6 (left)**	**+6 (right)**
Temporal offset(ms)		**10**	**10**
Wn frequency	**Low**	7.20	6.70
		0.30	*0.30*
	High	7.40	6.70
		0.30	*0.25*

Table 3.2. SL during the engagement phase in Experiment 2. Average saccade lengths (SL; in characters) from the first fixation on target words (here, Wn) during the engagement phase, shown for left and right probes, broken down for high- and low-frequency words. Standard errors of the means are shown in italics.

3.3.2.7 Saccade lengths and the effects of the presence/absence of the probe

A 2 (frequency: low and high) X 2 (probe status: present and absent) repeated-measures ANOVA was run on saccade lengths. The average number of accepted trials per condition per participant was 37.45 (*SEM* = 0.94) samples for the probe-absent condition (i.e., the control trials) and 24.78 (*SEM* = 0.77) for the probe-present condition. There was a marginal effect of frequency ($F(1,21) = 3.86$, $p = 0.06$, $\eta^2 = 0.04$): the average saccade length was 7.12 characters (*SEM* = 0.25) and 7.36 characters (*SEM* = 0.34) for low- and high-frequency words, respectively; however, the statistical power was low (power = 0.46). There was an effect of probe status ($F(1,21) = 7.87$, $p = 0.010$, $\eta^2 = 0.13$): the average saccade lengths was 7.03 characters (*SEM* = 0.13) and 7.45 characters (*SEM* = 0.13) with and without a probe, respectively. Therefore, the probe shortened the saccades. There was no interaction ($p = 0.24$).

3.3.2.8 Saccade lengths in Experiments 1 and 2, a comparison

We compared the effects of peripheral probes with a temporal offset of 10 ms (in Experiment 2) with those with a temporal offset of 40 ms (in Experiment 1) on saccade lengths. To do so, we ran a 2 (temporal offset: 10 ms and 40 ms) X 2 (spatial offset: -6 and +6) X 2 (frequency: low and high) mixed-design ANOVA with temporal offset as a between-subject variable on saccade lengths. There was an effect of spatial offset (*p* = 0.001) but no effect of frequency (*p* = 0.539) or temporal offset (*p* = 0.591); there was no interactions (*p* > 0.05).

So far, we provided the results of attention and eye movements for the engagement phase. In the following, we provided the results for the orienting phase (temporal offsets of 180 ms and 220 ms, spatial offsets of -6, 0 and +6 characters).

3.3.3 The orienting phase

Trials where the probe occurred with spatial offsets of 0, - 6 or + 6 characters and temporal offsets of 180 ms or 220 ms were included. From a total number of 4035 such trials, 3360 (83%) met the filtering criteria. The average number of accepted trials per condition per participant was 12.8 (*SEM* = 0.30) samples. A 2 (frequency: low and high) X 3 (spatial offset: - 6, 0 and + 6) X 2 (temporal offset: 180 ms and 220ms) repeated-measures ANOVA evaluated effects of spatial and temporal offsets and word frequency on error rates, first fixation durations on target words (here, Wn) and saccade lengths from these fixations.

Similar to the engagement phase, for fixation durations and saccade lengths, we also investigated the effects of probe status (the presence/absence of the probe) and ran a 2 (frequency: low and high) X 2 (probe status: present and absent) repeated-measures ANOVA on first fixation durations and saccade lengths.

3.3.3.1 Error rates

The average error rates are shown in Figure 3.2. A 2 (frequency: low and high) X 3 (spatial offset: - 6, 0 and + 6) X 2 (temporal offset: 180 ms and 220ms) repeated-measures ANOVA showed an effect of spatial offset ($F(2,42) = 28.86$, $p = 0.001$, $\eta^2 = 0.18$): the average error rate was 25.78% (*SEM* = 2.02) for left, 29.50% (*SEM* = 2.03) for central and 15.93% (*SEM* = 2.14) for right probes. Pairwise comparison with Bonferroni correction showed significant difference between right and central probes (*p* = 0.001) and right and left probes (*p* = 0.001) but not between central and left probes (*p* = 0.207). Therefore, as expected, attention was more on the right side of the gaze than the left side. There was an effect of temporal offset ($F(1,21) = 15.39$, $p = 0.001$, $\eta^2 = 0.03$): the average error rate was 21.3% (*SEM* = 1.8) and 26.1% (*SEM* = 1.9) for temporal offsets of 180 ms and 220 ms, respectively. There was no interaction between

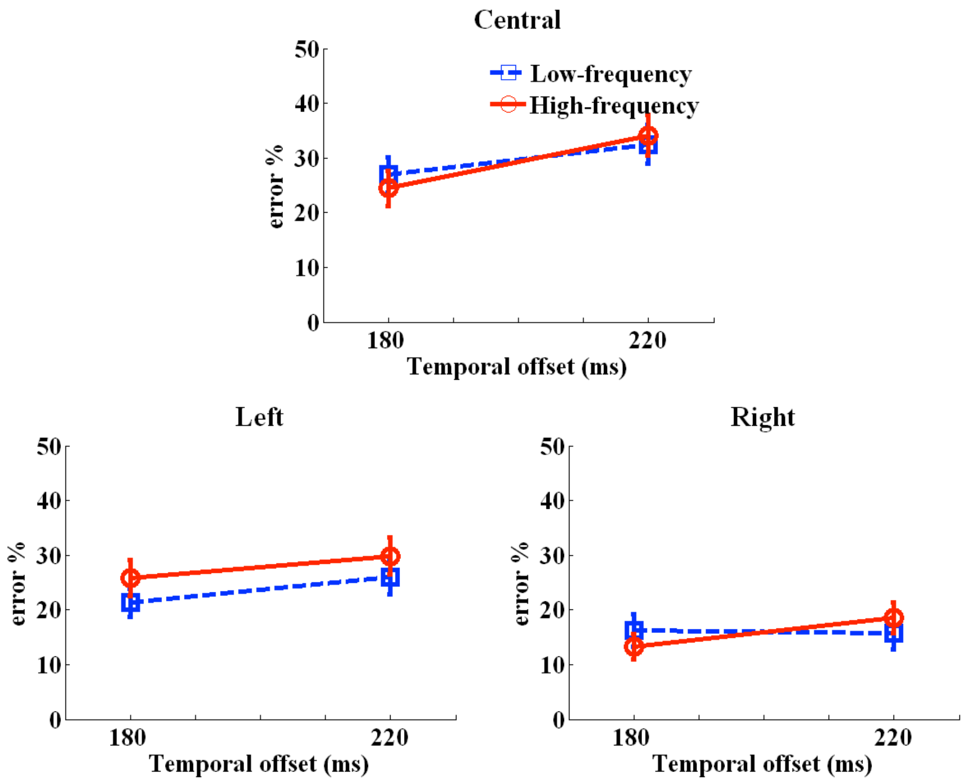

Figure 3.2. Error rates during the orienting phase in Experiment 2. Error rates on probe discrimination as a function of temporal offset of the probe during the orienting phase. Performance is broken down for low-frequency (dashed blue line) and high-frequency (solid red line) words. Error bars show one standard error of the mean. Data for central probes is shown in the top panel. Data for left probes is shown in the bottom-left panel and data for right probes is shown in the bottom-right panel.

the spatial and temporal offsets of the probe (p = 0.34). As an a-priori hypothesis, we looked at the effect of temporal offset for 'left and central' and right probes, separately. For 'left and central probes', we ran a 2 (frequency: low and high) X 2 (spatial offset: -6 and 0) X 2 (temporal offset: 180 ms and 220ms) repeated-measures ANOVA on error rates. We found an effect of temporal offset ($F(1,21) = 12.60$, $p = 0.002$, $\eta^2 = 0.05$): the average error rate was 24.63 % (*SEM*=1.83) and 30.62 % (*SEM* = 2.09) for temporal offsets of 180 ms and 220 ms, respectively. Thus, performance on left and central probes decreased from 180 ms to 220 ms into a fixation. For right probes, we ran a 2 (frequency: low and high) X 2 (temporal offset: 180 ms and 220ms) repeated-measures ANOVA on error rates. The effect of temporal offset was not significant ($F(1,21) = 2.29$, $p = 0.14$): the average error rate was 14.76 % (*SEM* = 2.23) and 17.10 % (*SEM* = 2.31) for temporal offsets of 180 ms and 220 ms, respectively. This is in line with our prediction that the decrease on probe discrimination from 180 ms to 220 ms into a fixation would be stronger for the left and central than right probes. This is evidence that over time, attention increased on the right side of the gaze and therefore compensated for the effects of saccadic suppression. We did not get any effect or interactions of frequency (all *p*-values > 0.36).

3.3.3.2 First fixation durations

The average durations of the first fixation on target words during the orienting phase are shown in Table 3.3. A 2 (frequency: low and high) X 3 (spatial offset: - 6, 0 and + 6) X 2 (temporal offset: 180 ms and 220 ms) repeated-measures ANOVA showed an effect of word frequency ($F(1,21) = 38.78$, $p = 0.001$, $\eta^2 = 0.12$): the average fixation duration was 359 ms (*SEM* = 14) and 326 ms (*SEM* = 12) for low- and high-frequency words, respectively. An effect of frequency on the duration of first fixation on target words confirmed that reading occurred.

There was an effect of spatial offset ($F(2,42) = 5.56$, $p = 0.007$, $\eta^2 = 0.07$). The average duration of first fixations was 346 ms (*SEM* = 16) for left, 355 ms (*SEM* = 16) for central and 326 ms (*SEM* = 11) for right probes. Pairwise comparison with Bonferroni correction showed no difference between left and central ($p = 0.911$) probes but a marginal difference between left and right ($p = 0.102$) and a significant difference between central and right ($p = 0.017$) probes. There was a marginal effect of the temporal offset of the probe ($F(1,21) = 2.97$, $p = 0.099$). The average fixation was 346 ms (*SEM* = 13) and 339 (*SEM* = 13) ms for temporal offsets of 180 ms and 220 ms, respectively.

There was a two-way interaction between word frequency and the spatial offset of the probe ($F(2,42) = 6.04$, $p = 0.005$, $\eta^2 = 0.03$). Given that there was an effect of frequency, we broke down this interaction for low- and high-frequency words. For low-frequency words, a 3 (spatial offset: -6, 0 and +6 characters) X 2 (temporal offset: 180 ms and 220 ms) repeated-measures ANOVA showed an effect of spatial offset ($F(2,42) = 7.36$, $p = 0.001$, $\eta^2 = 0.14$): average duration of the first fixation was 373 ms (*SEM* = 19) for left and 369 ms (*SEM* = 17) for central and 335 ms (*SEM* = 12) for right probes.

Pairwise comparison with Bonferroni correction showed a significant difference between left and right probes (p = 0.001) and central and right probe (p = 0.001). For high-frequency words, a 3 (spatial offset: - 6, 0 and + 6 characters) X 2 (temporal offset: 180 ms and 220 ms) repeated-measures ANOVA showed an effect of spatial offset ($F(2,42) = 3.46$, $p = 0.034$, $\eta^2 = 0.08$): average duration of the first fixation was 320 ms (*SEM* = 14) for left, 341 ms (*SEM* = 15) for central and 317 ms (*SEM* = 12) for right probes; however, the statistical power was low, power = 0.64. Pairwise comparison with Bonferroni correction did not show a significant difference between different offsets (p > 0.09). Therefore, only for low-frequency words ‘left and central’ probes prolonged the fixation more compared with right probes. This is compatible with an earlier start of the non-labile stage of saccade programming when the fixated word is high rather than low in frequency. There was no other reliable effects or interactions (p > 0.05).

Average FFD on target words (Wn)							
Spatial offset (characters)		**-6 (left)**		**0 (centre)**		**+6 (right)**	
Temporal offset(ms)		**180**	**220**	**180**	**220**	**180**	**220**
Wn frequency	**Low**	371	375	373	366	337	334
		21	*19*	*19*	*18*	*13*	*12*
	High	334	307	342	342	323	312
		17	*13*	*17*	*16*	*12*	*13*

Table 3.3. FFD on target words during the orienting phase in Experiment 2. Average first fixation durations (FFD) on target words during the orienting phase, shown for left, central and right probes with temporal offsets of 180 ms and 220 ms. Mean fixation durations are shown for high- and low-frequency words. Standard errors of the means (SEM) are shown in italics.

3.3.3.3 Fixation durations and the effects of the presence/absence of the probe

A 2 (frequency: low and high) X 2 (probe status: present and absent) repeated-measures ANOVA was run on the average of the duration of first fixations. The average number of accepted trials per condition per participant was 37.45 (*SEM* = 0.94) samples for the probe absent condition and 76.36 (*SEM* = 1.81) for the probe present condition. There was an effect of probe status ($F(1,21) = 50.76$, $p = 0.001$, $\eta^2 = 0.40$): the average duration of the first fixation was 343 ms (*SEM* = 13) and 306 ms (*SEM* = 10) for the probe-present and probe-absent conditions, respectively. There was an effect of word frequency ($F(1,21) = 40.86$, $p = 0.001$, $\eta^2 = 0.23$): the average duration of the first fixation on target words was 338 ms (*SEM* = 31) and 311 ms (*SEM* = 11) for low- and high-frequency words, respectively. There was no interaction ($p = 0.203$, power = 0.23). Thus, the probe did not interfere with the effects of frequency on fixation durations.

3.3.3.4 Saccade lengths

The average saccade lengths from the first fixation on target words are shown in Table 3.4. The average saccade length was 7.3 characters (*SEM* = 0.23). A 3 (spatial

Average SL from Wn (characters)							
Spatial offset		**-6 (left)**		**0 (centre)**		**+6 (right)**	
Temporal offset		**180**	**220**	**180**	**220**	**180**	**220**
Wn frequency	**Low**	7.35	7.77	7.21	7.18	6.65	6.98
		0.28	*0.31*	*0.28*	*0.29*	*0.25*	*0.29*
	High	7.38	7.52	7.46	7.42	7.12	7.33
		0.33	*0.25*	*0.26*	*0.27*	*0.28*	*0.26*

Table 3.4. SL during the orienting phase in Experiment 2. Average saccade lengths (SL) from the first fixations on Wn (target words) during the orienting phase, shown for left, central and right probes with temporal offsets of 180 ms and 220 ms. Mean saccade lengths are shown for high- and low-frequency target words. Standard errors of the means (SEM) are shown in italics.

offset: - 6, 0, + 6 characters) X 2 (temporal offset: 180 ms and 220 ms) X 2 (frequency: low and high) repeated-measures ANOVA showed a marginal effect of frequency ($F(1,21) = 3.58$, $p = 0.072$, $\eta^2 = 0.01$); however, the statistical power was low (0.43):

the average saccade length was 7.18 (*SEM* = 0.24) and 7.37 (*SEM* = 0.22) for low- and high-frequency words, respectively, which was in the expected direction.

There was an effect of spatial offset ($F(2,42) = 13.83$, $p = 0.001$, $\eta^2 = 0.06$): the average saccade lengths was 7.50 characters (*SEM* = 0.23) for left and 7.31 characters (*SEM* = 0.23) for central and 7.02 characters (*SEM* = 0.24) for right probes. Pairwise comparison with Bonferroni correction showed significant difference between left and right ($p = 0.001$) and central and right ($p = 0.001$) probes: saccade length was shorter after a right probe compared to a left or central probe. There was a marginal effect of temporal offset ($F(1,21) = 3.23$, $p = 0.085$, $\eta^2 = 0.01$); however, the statistical power was low (0.40): the average saccade length was 7.19 (*SEM* = 0.24) and 7.26 (*SEM* = 0.22) characters for temporal offsets of 180 ms and 220 ms, respectively.

3.3.3.5 Saccade lengths and the effects of the presence/absence of the probe

A 2 (frequency: low and high) X 2 (probe status: present and absent) repeated-measures ANOVA was run on saccade lengths. The average number of accepted trials per condition per participant was 37.45 (*SEM* = 0.94) samples for the probe absent condition and 76.36 (*SEM* = 1.81) for the probe present condition. The effect of probe status was marginal and weak ($F(1,21) = 3.11$, $p = 0.09$, statistical power = 0.39). The average saccade length was 7.21 (*SEM* = 0.22) and 7.46 (*SEM* = 0.24) characters for the probe-present and probe-absent conditions, respectively. Thus, probes shortened the saccades but not significantly. There was an effect of frequency ($F(1,21) = 7.31$, $p = 0.013$, $\eta^2 = 0.11$): the average saccade length was 7.21 characters (*SEM* = 0.24) and 7.51 characters (*SEM* = 0.24) for low- and high-frequency words, respectively. There was no interaction. The results suggest that probes occurring late in a fixation (with temporal offsets of 180 ms and 220 ms) did not (i) significantly shorten the saccades, or (ii) overwrite the effects of frequency.

3.4 Discussion

As we expected, the probe, as an abrupt-onset stimulus, prolonged the duration of first fixation on target words. Nevertheless, the effect of frequency on these fixations did not interact with the presence or absence of the probe. For both engagement and orienting phases, there was an effect of frequency on the duration of first fixation on target words. Therefore, reading occurred.

In the absence of the probe, saccades from the first fixations on target words were on average shorter when the fixated word was low rather than high in frequency. Thus, an effect of frequency on saccade lengths in the presence of the probe (i) does not mean that task priorities were changed and (ii) further supports that reading occurred. It should be noted that an effect of frequency on saccade lengths is compatible with observed behaviour in reading (e.g., Pollatsek & Rayner, 1990) but no effect of frequency on saccade lengths does not mean that reading did not occur.

3.4.1. Attention

Attention was asymmetric around the gaze location from very early in a fixation (i.e. at temporal offsets of 10 ms). The amplitude of attention, 6 characters from the gaze location, increased from 10 to 40 ms into the fixation; thus, we concluded that attention defocused from the beginning of the fixation. The effect of frequency on the amplitude of attention, 6 characters from the gaze location, was weak but was in the expected direction; thus, we concluded that attention was focused on the gaze more for low- than high-frequency words, from 10 ms in a fixation. The effect of frequency did not interact with spatial offset. This is in line with a more focused attention 10 ms than 40 ms into a fixation so that both left and right probes were sensitive to the frequency effect.

During the orienting phase, attention oriented towards the right. From 180 ms to 220 ms into a fixation, there was a decrease in probe discrimination. An *a*-priori comparison showed that this decrease was mostly for probes occurring at the gaze location or 6 characters to the left of the gaze but not for probes occurring 6 characters to the right. This is evidence that from 180 ms to 220 ms into a fixation, attention oriented (i) away from the gaze location and the left side of the gaze and (ii) towards the right side. Consequently, probe discrimination dropped stronger for left and central probes, where the effects of the orienting of attention and saccadic suppression (Haber & Hershenson, 1973) function in the same direction, than right probes, where the effects of the orienting of attention and saccadic suppression function in opposite directions. The results provided evidence of an orienting of attention towards the right from 180 ms to 220 ms into a fixation.

We did not find an effect of frequency on the orienting of attention for temporal offsets of 180 ms and 220 ms. It is possible that any effect of frequency was overwritten by the effects of saccadic suppression. In other words, it is possible that there was an effect (or interaction) of frequency but it was not revealed. It is also possible that 220 ms into a fixation, the orienting of attention is no longer affected by the load (frequency) of the *fixated* word. Processing of the upcoming word starts while the eyes are still fixating the current word (e.g., Rayner, 1975 a, 1975 b). Thus, it is possible that, towards the end of the orienting phase, attention is engaged with the processing of the upcoming word and, therefore, is affected by processing load of the upcoming, as opposed to the fixated, word.

3.4.2. Eye-movement behaviours

In line with the results in Experiment 1, right probes, compared to left or central probes, prolonged the fixations less and shortened the saccades more during both engagement and orienting phases. This is because right probes occurred in the direction of the upcoming saccade. Thus, compared to probes occurring at the gaze location or to the left of the gaze, right probes (i) interfered with the timing of the upcoming saccades less (Fischer, 1999; Reingold & Stampe, 2000, 2004) and (ii) competed with the intended saccadic target more (Coren & Hoenig, 1972; Deubel, Wolf & Hauske, 1984; Fischer, 1999).

During the engagement phase, there was no effect of temporal offset in terms of fixation durations and saccade lengths for probes occurring with temporal offset of 10 ms (in Experiment 2) and 40 ms (in Experiment 1) into the fixation. During the orienting phase (i.e., temporal offsets of 180 ms and 220 ms), there was a marginal effect of temporal offset on fixation durations and saccade lengths. Probes occurring 220 ms into the fixation (i) prolonged the fixations or (ii) shortened the upcoming saccades, less than to those occurring 180 ms. Given that both effects were only marginally significant, the results suggest that on average probes occurring 180 ms or 220 ms into the fixation, occurred close to the non-labile stage (Becker & Jürgens ,1979) of saccade programming.

In addition, during the orienting phase, the probe was more likely to occur close to the non-labile stage of saccade programming (Becker & Jürgens ,1979) when the fixated word was high rather than low in frequency. This was evidenced by an interaction between frequency and spatial offset in terms of fixation durations. For low-frequency words, left and central probes prolonged the fixation more than right probes. For high-frequency words, on the other hand, there was no difference between ‘left and central’ probes and right probes. This is compatible with an earlier start of the non-labile stage of saccade programming when the fixated word is high rather than low in frequency. This is also in line with an earlier orienting of attention, followed by a saccade, when the fixated word is high rather than low in frequency.

In Experiment 1, during the orienting phase (i.e., at temporal offsets of 110 ms, 130 ms and 180 ms), there was an effect of frequency on saccade lengths but only for right probes. In Experiment 2, during the orienting phase (i.e., temporal offsets of 180 ms and 220 ms), the effect of frequency on saccade lengths was marginal and did not interact with spatial offset. Therefore, these probes occurred sufficiently late to preserve the effects of frequency on the metrics of the upcoming saccade. Nevertheless, the absolute length of these saccades was still affected by the location of the probe: saccades were shorter for right than left probes.

3.5. Next experiment

In Experiment 1, 40 ms into a fixation, there was an effect of frequency on attention revealed by left probes. In Experiment 2, 10 ms into a fixation, the effect of frequency on attention was in the expected direction: attention was focused on the gaze more when the fixated word was low rather than high in frequency. Such an early effect of the frequency of the fixated word on attention is presumably because, in active reading, processing of the word starts before it is fixated (preview; Rayner, 1975a, 1975b). Thus, early in a fixation, processing of a word, at levels that correspond to its frequency, was sufficiently advanced to affect attention. It is possible that the processing of the upcoming word is sufficiently advanced to affect attention during its preview when attention is presumably engaged with its processing.

It is known that at least processing of the beginning letters of a word occur during preview (e.g., Rayner, 1982) and it affects where the eyes land on the word (e.g., Hyönä, 1995; Radach et al., 2004; White & Liversedge, 2006). Therefore, we proposed that at least the processing of the beginning letters of the upcoming word would be sufficiently advanced to affect attention before the word is fixated. In Experiment 3, we investigated the effects of processing load of target words on attention, shortly before the words were fixated.

Supplementary Information B

Did participants in Experiments 1 and 2 employ different strategies?

B.1 Introduction

In Experiment 1, the probe occurred in *all* trials. In Experiment 2, on the other hand, in some trials (i.e., in the control trials) the probe did not occur. Therefore, it is possible that participants in Experiment 1 adopted a different strategy to perform the primary and/or the secondary task compared to participants in Experiment 2. This being the case, one might argue that the observed difference between the accuracy of the discrimination of probes occurring 10 and 40 ms into a fixation (see section 3.3.2.2) does not represent an effect of temporal offset; rather, it represents an effect of different strategies in the two experiments.

If participants adopted different strategies and the difference between the strategies affected their performance on the probe or their eye movements, we would expect to see an effect of experiment (i.e., Experiment 1 versus 2) on eye movements, before the probe occurred, or on the accuracy of probe discrimination for probes occurring with the same spatial and temporal offsets in Experiment 1 compared to Experiment 2.

To address this, we first compared eye movement behaviour, in Experiments 1 and 2, before the probe occurred. Hence, we compared the length of saccades into the target words and the duration of the last fixation before the eyes landed on target words in Experiments 1 and 2. Then, we compared the performance on the probe and the effect of the probe on fixation durations on target words and saccade lengths from these fixations in those trials in Experiments 1 and 2 in which the probe occurred with a temporal offset of 180 ms. We chose the temporal offset of 180 ms because both experiments included this temporal offset. We expected that there should be no effect of experiment on eye-movement behaviours or on the accuracy of the discrimination of the probe if participants' strategy was not different in Experiments 1 and 2.

B.2 Analysis

B.2.1 Participants' behaviour before the probe occurred

In Experiments 1 and 2, the probe occurred after the eyes landed on target words. Therefore, the last fixation before the eyes landed on target words and saccade lengths into target words were not affected by the probe. We analysed all trials in Experiments 1 and 2 where (i) the target word was fixated for at least 100 ms and (ii) this fixation was followed by a forward saccade. Twenty-two participants from each experiment were included. Then, we ran a one-way ANOVA with experiment as a between-subject factor on the average duration of the last fixations before the eyes landed on target words and the length of saccades that were made into the target words.

B.2.1.1 Duration of the last fixation before the eyes landed on target words

The average duration of the last fixation was 271 ms (*SEM* = 8) and 279 ms (*SEM* = 8) in Experiments 1 and 2, respectively, and the difference was not significant ($p = 0.215$).

B.2.1.2 Saccade lengths into target words

The average saccade lengths were 7.72 (*SEM* = 0.18) characters for participants in Experiment 1 and 7.90 (*SEM* = 0.23) characters for participants in Experiment 2 and the difference was not significant ($p = 0.539$).

B.2.2 Participants' behaviour after the probe occurred

We analysed the duration of the first fixation on target words and saccade lengths from these fixations for those trials in which the probe occurred with a temporal offset of 180 ms in Experiments 1 or 2. Furthermore, we analysed the accuracy of probe discrimination in these trials. We ran a 2 (experiment: Experiments 1 and 2) X 3 (spatial offset: -6, 0 and +6) X 2 (frequency: low and high) mixed-design ANOVA, with experiment as a between-subject variable on first fixation durations and saccade lengths and error rates. Here, we only report p-values that are relevant to the effect of, or interactions with, experiment.

B.2.2.1 First fixation durations

There was no effect of experiment ($p = 0.503$). There was no interaction ($p > 0.05$).

B.2.2.2 Saccade lengths

There was no effect of experiment ($p = 0.973$). There was no interaction ($p > 0.05$).

B.2.2.3 Error rates

There was no effect of experiment ($p = 0.908$). There was no interaction ($p > 0.05$).

B.3 Discussion

We did not find any effects of experiment on participants' behaviour before or after the probe occurred. Therefore, we did not find any evidence to suggest that participants' strategy in Experiment 2 was different from participants' strategy in Experiment 1. Hence, the difference in the accuracy of the discrimination of probes occurring 10 ms (trials from Experiment 2) and probes occurring 40 ms (trials from Experiment 1) into a fixation was not due to different strategies between the two experiments; rather, this difference represents an effect of the temporal offset of the probe. In other words, 6 characters from the gaze location, the amplitude of attention increased from 10 ms to 40 ms into a fixation. Thus, we conclude that attention defocused from the very beginning of a fixation.

Chapter 4

Effects of the load of the upcoming word on attention

4.1 Introduction

Results from Experiments 1 and 2 showed that, early in a fixation, processing of a word was sufficiently advanced to reveal an effect of its frequency on the focus of attention (Ghahghaei et al., 2013). This is presumably because participants obtained a benefit from previewing the word before fixating on it. In other words, before the word was fixated, processing of the word started (e.g., Rayner, 1975a, 1975b) and, consequently, attention engaged with the word. Although there are many reports that processing of the upcoming word affects programming of the saccade to the word (Doré-Mazars et al., 2004; Heller, 2004; Hyönä, 1995; Vonk et al., 2000; White & Liversedge, 2006), it is not clear whether this processing also affects attention before the word is fixated. In Experiment 3, we addressed whether the load of the upcoming word affects attention by manipulating its frequency and the orthographic familiarity of its first trigram (i.e., the first three letters).

It is known that the beginning letters in a word are usually processed before it is fixated. For example, Zola (1980) showed that valid preview of the leading letter of a word is helpful for reading. Using a moving-window paradigm, Rayner et al., (1982) showed that when the fixated word and the first three letters of the next word are preserved, but other letters are masked, the speed of reading does not change compared to when none of the letters are masked. Thus (i) processing of the upcoming word begins before it is fixated, so that denying valid preview of the word slows down reading, and (ii) processing of the beginning three letters is especially important.

In addition to studies showing a benefit from previewing a word in terms of reading time, studies on where the eyes land on a word support the idea that processing of the beginning letters in a word occurs before the word is fixated; namely, it affects the decision on where to land the eyes on the word. For example, the eyes land closer to the beginning of the word that has a more irregular combination of the beginning letters (Heller, 2004; Hyönä, 1995; Vonk et al., 2000). In addition, Vonk et al. (2000) showed that orthographic familiarity of first trigrams in target words affected where the eyes landed on them: the more unfamiliar the first trigrams were orthographically the closer the eyes landed to the beginning of the words.

White and Liversedge (2006) showed that the landing position on the upcoming word (i) is affected by its orthography, but (ii) is not affected by the load of the currently fixated word. Specifically, they manipulated two words (i.e., Wn and Wn+1) in a sentence. They manipulated Wn to be high or low in frequency. They manipulated the second letter in Wn+1 to be correctly spelled (thus, orthographically familiar) or misspelled (thus, orthographically unfamiliar). Their results showed that the landing position on Wn+1 was shifted towards the beginning of the word for orthographically unfamiliar words, independent of the frequency of Wn. Hence, where the eyes landed on the upcoming word was affected by the orthography of its beginning letters but not the frequency of the fixated word.

Furthermore, there is no evidence of an effect of the frequency of the upcoming word (Wn+1) on where the eyes land on it. For example, White (2008) study addressed whether the frequency or the orthographic familiarity of the *whole word* affects the landing position on the word. The author manipulated both frequency of target words and orthographic familiarities of the whole word (not only the beginning letters)[12]. The results showed no effect of the orthographic familiarity of the whole word or the frequency of the word on landing positions. In line with this, Plummer and Rayner (2012) found no effect of the lexicality of the upcoming word/non-word in the line of text on where the eyes landed on it; Nevertheless, they did find an effect of the orthographic familiarity of the first trigrams in the upcoming word/non-word on where the eyes landed on that word/non-word. This is in line with White and Liversedge's

[12] They manipulated the familiarity of n-grams in target words to be low or high. The orthographic familiarity of first trigrams was low for the low-orthography and high for the high-orthography n-gram group.

(2006) study that when the beginning sequence of letters in a word was misspelled, the landing position shifted towards the beginning of the word.

In sum, the landing position on the upcoming word (i) is affected by the orthographic familiarity of its first trigram, (ii) is not necessarily affected by the orthographic familiarity of the whole word, (iii) is not affected by its frequency, and (iv) is not affected by the frequency of the fixated word. Thus, in line with preview benefit being mostly obtained from the first trigram in the upcoming word (Rayner et al., 1982), it is the orthographic familiarity of the first trigram in the word that affects where the eyes would land on it. Frequent letter sequences may look visually more familiar than infrequent letter sequences (Findlay & Walker, 1999). This in turn may ease the processing of the sequence. When the processing of the beginning sequence of letters in a word is more demanding, the eyes are presumably attracted to the beginning of the word more, presumably, to help gather more information.

We proposed that, when processing of the beginning sequence of letters in the upcoming word is more demanding, attention would be engaged more with this processing and, thus, would be allocated more to the upcoming word, shortly before the saccade to the upcoming word. We investigated effects of the processing of the upcoming word on attention, in Experiment 3, by orthogonally manipulating the frequency of these target words and the orthographic familiarities of their first trigrams, using a subset of the stimulus set that we used in Experiments 1 and 2. We refer to this stimulus set as the *frequency/orthography stimulus set* (see section 4.2.3.1 for details).

We probed attention, at the gaze location, shortly before the eyes fixated on these target words; see Figure 4.1. In this experiment (Experiment 3) we refer to the target word as Wn+1 and to the word that preceded the target word as Wn. The probe occurred with varying temporal offsets from the beginning of the first fixation on Wn. We only analysed trials in which there was a single fixation on Wn followed by a saccade to Wn+1 (i.e., the target word). Relatively late temporal offsets (i.e., 180 ms, 220 ms or 250 ms) were chosen given that the average duration for a single fixation is longer than the average duration for the first/last fixation of multiple fixations on a word (e.g., Sereno, Pacht & Rayner, 1992). To ensure that the probe occurred sufficiently late, we only analysed trials in which the probe-onset occurred within the last 100 ms of this single fixation on Wn.

We only probed attention at the gaze location but not on the left or right side of the gaze. This was because (i) by requiring a single fixation on Wn the filtering criteria in Experiment 3 was more conservative than the criterion used in Experiments 1 and 2 and (ii) the frequency/orthography stimulus set was only a subset of the stimulus set used in Experiments 1 and 2. Consequently, we did not have sufficient samples in the frequency/orthography stimulus set for each level of load manipulation (see Methods, section 4.2) to include central *and* peripheral probes. Thus, Experiment 3 was a 3 (temporal offset: 180 ms, 220 ms and 250 ms) X 2 (frequency of Wn+1: low and high) X 2 (orthographic familiarity of the first trigram in Wn+1: low and high) repeated-measures design.

We now sharpen our predictions in terms of attention, measured by the accuracy of probe discrimination. Given that we only analysed trials in which the probe-onset occurred during the last 100 ms of a single fixation on Wn, we did not expect an effect of temporal offset on accuracy of probe discrimination. This is because the information on temporal offset was already taken into account to ensure that the probe occurred shortly before the saccade to the target word (here, Wn+1).

We expected that, shortly before a saccade to Wn+1, attention would be allocated to Wn+1 more when its processing was more demanding. Given that (i) the eyes land closer to the beginning of a word when its first trigram is less familiar and (ii) processing of a word, even at levels that correspond to its orthography, demands spatial attention (e.g., Waechter et al., 2011), we expected poorer performance on central probes (i.e., probes occurring at the gaze location and on Wn) when the orthographic familiarity of the first trigram in Wn+1 (i.e., the target word) was low rather than high.

This prediction also holds for any effects of the frequency of Wn+1 on attention. In spite of no reports of an effect of the frequency of the upcoming word on where it is fixated, it is possible that the word's frequency affects attention before it is fixated. This being the case, we would expect poorer discrimination of central probes when the target word (Wn+1) was low rather than high in frequency.

A word's processing at those levels that correspond to its frequency should occur no earlier than its processing at those levels that correspond to the orthographic familiarity of its first trigram. Therefore, we proposed that any effects of frequency on attention, at the gaze location, should be no earlier than any effects of the orthographic familiarity of the first trigram.

We now sharpen our predictions in terms of eye-movement behaviours. To ensure that reading occurred, we analysed the duration of first fixations on target words (Wn+1). We did not expect an effect of the orthographic familiarities of the first trigrams in target words on the duration of first fixations on target words because there is no report of that, to the best of our knowledge, in the literature. On the other hand, we expected an effect of the frequency of target words on the duration of first fixations on them to ensure that reading occurred (Rayner & Raney, 1996).

To be consistent with the analysis in Experiments 1 and 2, we analysed the duration of single fixations on Wn (in this experiment, the words that preceded the target words) and the length of the forward saccades that were made from these fixations (in this experiment, the saccades to the target words). In the process of making the stimulus set used in Experiments 1 and 2, the words that preceded target words were chosen not to be low in frequency. Thus, in Experiment 3, the load of Wn was not manipulated. Nevertheless, it is possible that the load of Wn+1affects fixation durations on Wn. This is because some studies have shown that the processing load of the upcoming word (i.e., Wn+1) can affect how long the eyes remain on the fixated word. For example, Drieghe, Brysbaert and Desmet (2005) showed that fixation durations on Wn were prolonged when Wn+1 was a long word. However, in the current experiment, it was not clear whether the processing load of the upcoming word (Wn+1; the target word) would affect the duration of a single fixation on the currently fixated word (Wn). In terms of the length of the saccade to the upcoming word (i.e., the saccade from Wn to Wn+1), to the best of our knowledge, there is no report of an effect of the load (its frequency and/or orthographic familiarity of its first trigram) of the upcoming word on the length of the first saccade to it. Therefore, we did not expect an effect of the frequency of the target word or the orthographic familiarity of its first trigram on the length of the saccade to the word.

On the other hand, we did expect to see an effect of the orthographic familiarity of the first trigrams in target words on landing positions on target words. We expected that this effect would be in the direction of effects that are reported in the literature: the less familiar are the first trigrams in target words, the more the landing positions on them should shift towards the beginning of the words (Heller, 2004; Hyönä, 1995; Vonk et al., 2000; White and Liversedge, 2006).

We addressed effects of the processing load of targets words on landing positions on them by analysing the subset of the data from *Experiments 1 and 2* derived from the frequency/orthography stimulus set used in Experiment 3 in which the frequency of target words and the orthographic familiarity of their first trigrams were orthogonally manipulated. We analysed data from Experiments 1 and 2, and *not* from

Experiment 3, because of a number of reasons. First, in Experiments 1 and 2, the probe occurred only after the eyes landed on target words. Thus, landing positions on target words were not affected by the probe. Second, there were more participants in Experiments 1 and 2, compared to Experiment 3, and this was helpful for the statistical power of the analysis. Third, in Experiment 3, compared to Experiments 1 and 2, fewer trials per participant were accepted because of more conservative filtering criteria. Overall, the statistical power of the analysis was higher when data from Experiments 1 and 2 rather than Experiment 3 was used. Thus, for landing positions only, we analysed data from Experiments 1 and 2 rather than Experiment 3.

The landing position of the saccade to the upcoming word is highly affected by the distance between the launch site of the saccade (i.e., the gaze location on the currently fixated word) and the beginning letter in the upcoming word. The bigger is the distance the more the landing position shifts towards the beginning of the upcoming word (Underwood, 1998). If the effect of this distance is not taken into account, any effects of orthographic familiarity might be overwritten. Hence, we broke down the analysis over the distance between the launch site and the target word. In sum, we analysed those trials in Experiments 1 and 2 in which (i) the sentence belonged to the frequency/orthography stimulus set, (ii) the target word was fixated for at least 100 ms, (iii) the first fixation on the target word was followed by a forward saccade, and (iv) the distance between the launch site of the saccade to the target word and the beginning letter in the target word was bigger than 3 and smaller than 8 characters[13]. A 4 (the distance between launch site and the beginning of the target word: 4, 5, 6 and 7 characters) X 2 (frequency of Wn: low and high) X 2 (orthographic familiarity of the first trigram in Wn: low and high) repeated-measures ANOVA[14] was run on landing position.

[13] The probability of skipping (i.e., not fixating) a word increases when the launch site is closer to the word. One possible reason for skipping the upcoming word is that the upcoming word was meant to be fixated instead of the currently fixated word but, because of some saccadic errors, the eyes landed short. In this case, although the upcoming word is not fixated, attention is engaged with its processing. Therefore, we did not include trials in which the launch site was too close to the target word. On the other hand, when the launch site is too far from the target word (e.g., further than 8 characters), the preview benefit from the upcoming word decreases because of a drop in acuity. Thus, we did not include trials in which the launch site was too far.

[14] Using ANOVA for this analysis was appropriate because we did not include trials with very small or very big launch site distance. So, there was not any bias in terms of the number of accepted trials

We expected that the bigger the distance between the target word and the launch site the more the landing position on the word would shift towards its beginning. In addition, we expected that the less familiar the first trigram in the target word was, orthographically, the more the landing position would shift towards the word's beginning. Given that, to the best of our knowledge, there is no report of an effect of frequency on landing positions, we did not expect an effect of frequency on landing position. An effect of the orthographic familiarity of the first trigrams on landing position would confirm that, within our stimulus set, processing of the target word, during preview, was sufficiently advanced to affect the programming of the saccade to the word.

4.2 Method

4.2.1 Participants

Twenty-five native mono-lingual English speakers participated in Experiment 3, all between 18 and 30 (19 female). According to their self-reports, they were students (mostly, Nursing, Psychology or Art students) from different universities in San Francisco. Participants received money for their participation.

Experiments 3, 4 and 5 were conducted at the Smith-Kettlewell Eye Research Institute in San Francisco. We had IRB (Institutional Review Board) approval from the institute in addition to Ethical approval from Goldsmiths, University of London, for all experiments.

4.2.2 Apparatus

The stimuli were displayed on a 21W ViewSonic G225f monitor. Same luminance as in London was used. Eye movements were recorded by an EyeLink 1000 eyetracker. The resolution of EyeLink II and EyeLink 1000 are similar. The same code

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for each level of the distance of the launch site. In addition, we had four separate levels for the four possible launch sites (i.e., 4, 5, 6, or 7 characters away) in our study. Furthermore, ANOVA has been used for the analysis of landing positions in previous studies (Rayner, McConkie & Ehrlich, 1978; Slattery, Staub & Rayner, 2011).

was used for the programming of the experiments as in London. The same device, gamepad, was used to log participants' response as in London. In sum, we believe that the experimental devices and set up we had in San Francisco were similar to those we had in London.

4.2.3 Stimuli

In Experiment 3, we used a so-called *frequency/orthography* stimulus set. For the analysis of landing positions in Experiments 1 and 2, we used data from a subset of trials where the stimuli (sentences) belonged to the frequency/orthography stimulus set. Below, we explained how we chose/made the frequency/orthography stimulus set.

4.2.3.1 The frequency/orthography stimulus set

In Experiments 1 and 2, we used an item-based stimulus set. Each item had two sentences that were identical except in their target words. Each participant was presented with only one sentence from each item: either the one that included a low-frequency target word or the one that included a high-frequency target word. In Experiment 3, we chose a subset of the item-based stimulus set based on the orthographic familiarity of first trigrams[15] in the target words. We defined a range for high orthographic familiarity and a range for low orthographic familiarity for the first trigrams in the target words- see Table 4.1. Then, we only included the items for which the orthographic familiarity of the first trigram in at least one of the item's target words belonged to our desired ranges of orthographic familiarities. We then divided these items into two groups: the low-frequency group and the high-frequency group. The low-frequency group included those items that we were *only* interested in their low-frequency target word. The high-frequency group included those items that we were *only* interested in their high-frequency target word. The reason is that, the orthographic familiarity of first trigrams in these low-frequency or high-frequency target words was within the ranges that we defined for low or high orthographic familiarities. For each item in the high-frequency group, we only kept the sentence where the target word was a high-frequency word; we discarded the other sentence. For each item in the low-frequency group, we only kept the sentence where the target word was a low-frequency

[15] We calculated the orthographic familiarities of the trigrams in the same way we calculated the frequencies of the words using the same corpus. For example, if the trigram was 'abc' and the corpus was {'abcd', 'abcd', 'abcf', 'ddab', 'dabc', seabc','seadc}, then orthographic familiarity of 'abc' would be 5.

word; we discarded the other sentence. Thus, we no longer had an item-based stimulus set; rather, we had sentences with either a high-frequency or a low-frequency target word. Then, we excluded all sentences where the target word was shorter than 5 characters or longer than 9 characters. Then we divided the low-frequency group into two sub-groups: the LH group where the first trigrams in target words were orthographically familiar (i.e., high orthography), and the LL group where the first trigrams in target words were orthographically unfamiliar (i.e., low orthography). Doing the same for the high-frequency group, we divided the group into two sub-groups: the HH group where the first trigrams in target words were orthographically familiar (high orthography), and the HL group where the first trigrams in target words were orthographically unfamiliar (low orthography). Consequently, we had four groups of sentences. For each group, frequency of the target word and orthographic familiarity of its first trigram was either low or high. This stimulus set was called the frequency/orthography stimulus set. Eighty-eight sentences were included in each group of the stimulus set. Table 4.1 shows the average log frequency of target words and orthographic familiarity of their first trigram. In the following, we present one sample sentence from each group in the frequency/orthography stimulus set. In each sentence, the target word is italicised only for illustration purposes.

(i) The LL group where the target word is low-frequency and its first trigram is orthographically low familiar.

`Shannon wore the brown` *`scarf`* `which she bought yesterday to the disco party.`

(ii) The LH group where the target word is low-frequency and its first trigram is orthographically high familiar.

`You will find that increased` *`outrage`* `over the problem only makes it worse.`

(iii) The HL group where the target word is high-frequency and its first trigram is orthographically low familiar.

`Next to the saloon an older` *`woman`* `tended to the horses.`

(iv) The HH group where the target word is high-frequency and its first trigram is orthographically high familiar.

`Despite the prolonged *search* for wild fruit, the campers were still hungry.`

Raw log frequency and log orthographic familiarity for target words in the frequency/orthography stimulus set					
Frequency	Orthographic familiarity				
			Average	Minimum	Maximum
Low	**Low (LL)**	LF	1.1	-3.51	2.68
		LOF	6.27	5.81	6.68
	High (LH)	LF	0.85	-4.61	2.82
		LOF	7.64	6.7	8.87
High	**Low (HL)**	LF	4.39	2.85	6.08
		LOF	6.32	5.81	6.68
	High (HH)	LF	4.52	2.99	6.03
		LOF	7.57	6.75	8.8

Table 4.1. Average raw log frequencies. Average raw log frequencies (LF) of target words and log orthographic familiarity (LOF) of the first trigram in target words in the frequency/orthography stimulus set. The data is shown for the LL, LH, HL and HH groups of the frequency/orthography stimulus set. For each group, the minimum, maximum and average values are provided.

4.2.4 Design

In Experiment 3, we were interested in whether the processing load of target words (Wn+1), before they were fixated, affected the orienting of attention from the gaze location on the preceding words (Wn). To do so, we looked at probe discrimination in trials where the probe occurred during a single fixation on Wn. Therefore, we chose our latest temporal offset to be shorter than the average single fixation duration on the words that precede the target words; see Box 4. 1.

On average, the duration of a single fixation on a word is not shorter than the duration of the last fixations on it (e.g., Sereno, Pacht & Rayner, 1992). Thus, when the latest temporal offset was smaller than the average of the last fixation durations on the words that precede the target words, it would also be smaller than the average of

Box 4.1 The duration of the last fixations before the eyes landed on target word

We only had access to the duration of three fixations: the fixation during which the probe occurred, and the fixations that immediately preceded or followed this fixation. We had information on gaze locations for each of these fixations. However, we only had information on word boundaries for Wn (which was the target word in Experiments 1 and 2, but was the word that preceded the target word in Experiment 3). It is possible that in Experiments 1 and 2, before the eyes landed on target words, the last fixation was not always on the preceding words. For example, it is possible that the preceding word was not fixated in some trials. We could not identify and exclude these trials in Experiments 1 and 2. Nevertheless, we expected that these trials would not be very common and that in the majority of the trials, the last fixation before the eyes landed on the target word would be on the word that preceded it.

We included a subset of trials in Experiments 1 and 2 where (i) the sentence belonged to the frequency/orthography stimulus set and (ii) the target word was fixated for at least 100 ms and (iii) this fixation was followed by a forward saccade. Duration of the last fixation before the eyes landed on the target word was analysed in a 2 (frequency: low and high) X 2 (orthographic familiarity of the first trigram: low and high) repeated-measures ANOVA. Forty-four participants were included in the analysis. We did not find any reliable effects or interaction. The average duration of this fixation was 284 ms (*SEM* = 7). The average duration of this fixation was 287 ms (*SEM* = 8) and 280 ms (*SEM* = 8) for low- and high-frequency target words, respectively. The average duration of this fixation was 281 ms (*SEM* = 7) and 286 ms (*SEM* = 8) when the first trigrams in target words were orthographically unfamiliar or familiar, respectively. Given that (i) we wanted the latest temporal offset to be shorter than the average fixation duration on the words that preceded the target words and (ii) the duration of the probe was 30 ms, we chose the latest temporal offset to be 250 ms.

single fixation durations on them. In a subset of trials in Experiments 1 and 2 where (i) the stimuli (sentences) belonged to the frequency/orthography stimulus set and (ii) the target word was fixated for at least 100 ms, the average duration of the last fixation before the eye landed on the target word was 284 ms (*SEM* = 7). Thus, considering that the duration of the probe was 30 ms, we chose a temporal offset of 250 ms as our latest probe.

In Experiment 3, the probe occurred when the eyes landed on the word that preceded the target word (Wn). The probe always occurred at the gaze location (spatial offset of 0 characters). It occurred with temporal offsets of 180 ms, 220 ms or 250 ms from the onset of the first fixation on Wn. Using the frequency/orthography stimulus set, we orthogonally manipulated the frequency of target words (Wn+1) and the orthographic familiarity of the first trigram in them. Consequently, Experiment 3 was a 3 (temporal offset: 180, 220 and 250 ms) X 2 (word frequency: low and high) X 2 (orthographic familiarity: low and high) repeated-measures design. For each level of the processing load (i.e., each group in the frequency/orthography stimulus set), there were three temporal offsets. Over all, each participant read a list of 348 sentences that were presented in a random order in terms of the temporal offset of the probe and the processing load of target words. Each participant read a different list and was presented with each condition 29 times. Given that we did not find any effects of the orientation of the probe (i.e., which side the probe was tilted) in Experiments 1 and 2, we no longer manipulated it. It was randomly chosen in each trial.

4.2.5 Procedure

Procedure in Experiment 3 was the same as in Experiment 1, except that during the long practice block, (i) the probe always occurred at the gaze location and with a temporal offset of 180 ms, and (ii) the luminance of the probe was adjusted for each participant to avoid the ceiling or floor effect. Experiment 3 was run in two sessions, separated by at least one hour. Figure 4.1 shows a schematic representation of one trial in Experiment 3. Note that probe occurred while the eyes were on the word that preceded the target word.

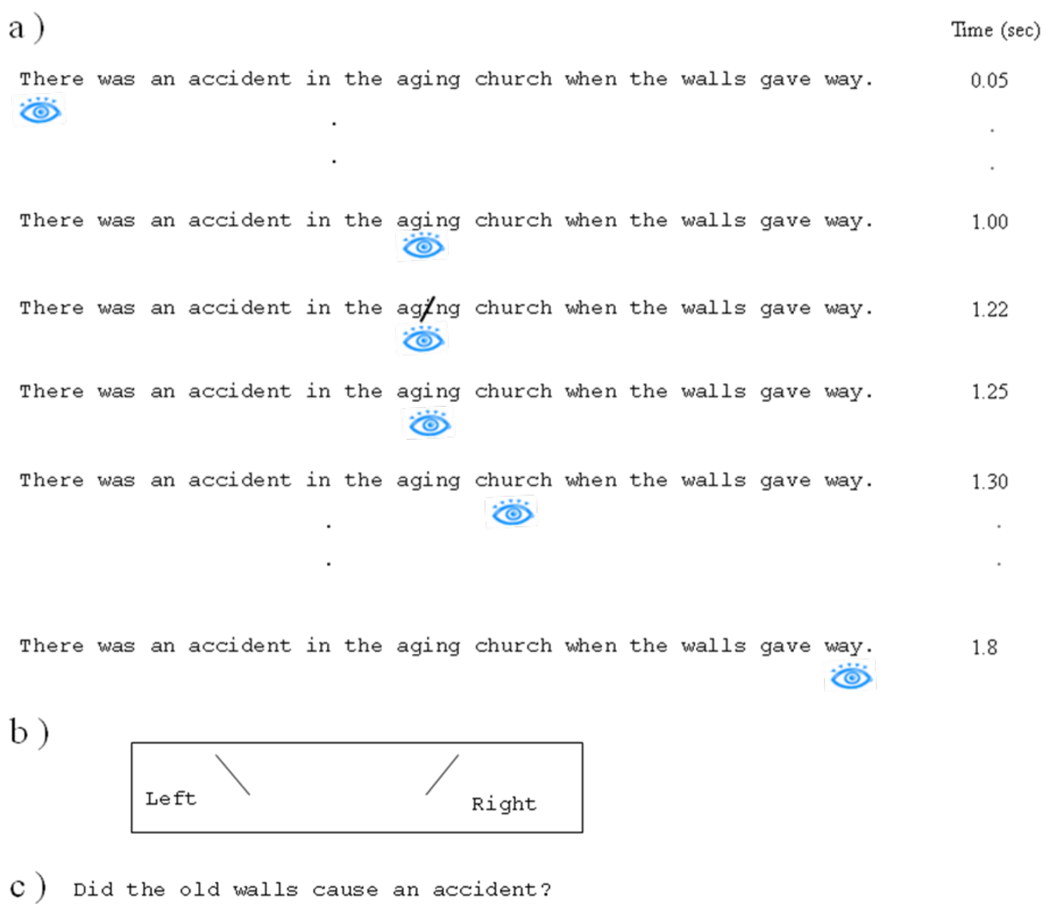

Figure 4.1. A schematic representation of one trial in Experiment 3. One sentence at a time was presented on the screen (a). Participants read the sentence in silence. There was a target word (Wn+1; here the word ‘church’) in each sentence. Wn was the word that preceded the target word, here the word ‘aging’. After some temporal offset from the beginning of the first fixation on Wn (here a temporal offset of 220 ms), the probe occurred at the gaze location. The probe was only presented for 30 ms. Participants were instructed to (i) try not to be distracted by the probe and (ii) continue reading. Participants were allowed to read the sentence only once. After the sentence disappeared, another screen appeared and asked them about the orientation of the probe (b). After the response to the probe was made, in 25 % of the trials, another screen appeared asking participants to verbally answer (‘yes’ or ‘no’) to a comprehension question on the sentence they had just read (c). : gaze location.

4.3 Results

In section 4.3.1, we address whether the processing of target words, during preview, was sufficiently advanced to affect where the eyes would land on them, using a subset of the data in *Experiments 1 and 2* in which the sentence belonged to the frequency/orthography stimulus set. In section 4.3.2, we provide the results of *Experiment 3*, where we address the effects of the processing load of target word on attention before the saccade to it. Error rates, single fixation durations on Wn, saccade lengths from Wn to Wn+1 and first fixation durations on Wn+1 were analysed for Experiment 3. It should be noted that Wn was the target word in Experiments 1 and 2 but the word that preceded the target word in Experiment 3.

4.3.1 Landing positions on target words in Experiments 1 and 2

The landing positions on target words in Experiments 1 and 2 were not affected by the probe. This is because the probe only occurred after the eyes landed on the target word. Data from 22 participants in Experiment 1 and 22 participants in Experiment 2 was analysed. We only included a subset of trials where (i) the stimuli (sentence) belonged to the frequency/orthography stimulus set, (ii) the target word was fixated for at least 100 ms, (iii) this fixation was followed by a forward saccade and (iv) the launch site was further than 3 and closer than 8 characters- the filtering criteria. Five participants from Experiments 1 and 2 did not have sufficient samples per condition and were excluded from the analysis. From the remaining (thirty-nine) participants, a total of 9,006 trials passed the first four filtering criteria.

As mentioned before, the distribution of the landing position on a word depends on the launch site. On average, the launch site in those trials that passed the first four filtering criterion was 5.52 characters (*SEM* = 0.81) away from the beginning of the target word. In 55.3 % of these trials, the launch site was 4 (in 1310 trials), 5 (in 1343 trials), 6 (in 1300 trials), or 7 (in 1033 trials) characters away. We only included the data from these trials because, (i) we did not have enough samples for other levels of the distance between the target word and the launch site and, (ii) we did not want to include trials where the launch site was too close to the target word or too far from the word– see footnote 13.

We ran a 4 (the distance between the launch site and the word: 4, 5, 6, and 7 characters) X 2 (frequency: low and high) X 2 (orthography: low and high) repeated-measures ANOVA on the landing position on target words. There were on average 7.6 (*SEM* = 0.4) samples per condition per participant.

Table 4.2 shows the average landing position on target words across different levels of the distance of the launch site, the frequency of target word and the orthographic familiarity of its first trigram. The average landing position was 2.15 (*SEM* = 0.12) characters. There was an effect of the distance of the launch site ($F(3,114) = 82.77$, $p = 0.001$, $\eta^2 = 0.29$): average landing position was 2.79 (*SEM* = 0.14) , 2.29 (*SEM* = 0.13), 1.92 (*SEM* = 0.12) and 1.60 (*SEM* = 0.12) characters for when the launch sites

Average landing position (LP) on target words in Experiments 1 and 2					
		Launch site distance to the target word			
		4	**5**	**6**	**7**
Target word frequency	Target word orthography				
Low	**Low (LL)**	2.63	2.20	1.81	1.61
		0.14	*0.16*	*0.13*	*0.18*
	High (LH)	2.91	2.39	2.12	1.72
		0.16	*0.15*	*0.15*	*0.16*
High	**Low (HL)**	2.77	2.19	1.79	1.59
		0.21	*0.17*	*0.17*	*0.17*
	High (HH)	2.87	2.39	1.98	1.50
		0.18	*0.18*	*0.16*	*0.11*

Table 4.2. LP on target words in Experiments 1 and 2. Average landing positions on target words in Experiments 1 and 2. Mean landing positions (in characters) are shown for LL, LH, HL and HH target words across launch sites that were 4, 5, 6 or 7 characters from the beginning of the target words. Standard errors of the means (SEM) are shown in italics.

was 4, 5, 6 and 7 characters from the target word, respectively. Pair-wise comparison with Bonferroni correction showed significant difference between all levels of the distance between the launch site and the target word ($p = 0.001$). Therefore, the further the eyes were from the beginning of target words before fixating on them, the closer the landing positions on target words were to the beginning of the words. There was a main effect of the orthographic familiarity of first trigrams in target words ($F(1, 38) = 9.42$, $p = 0.004$, $\eta^2 = 0.01$): the average landing position was 2.07 (*SEM* = 0.12) and 2.23 (*SEM* = 0.12) characters for words beginning with orthographically unfamiliar and familiar trigrams, respectively. There was no effect of frequency ($p = 0.475$). There was no interaction (all *p*-values > 0.173). Thus, the more unfamiliar the first trigrams were orthographically, the closer the eyes landed to the beginning of the words.

4.3.2 Results for Experiment 3

Participants who had less than 10 % or more than 40% error on probe discrimination, 7 participants, were excluded and data from the remaining 18 participants were included. Trials were included if they met the following filtering criterion: (i) there was only a single fixation on the word that preceded the target word, Wn, (ii) probe-onset occurred within the last 100 ms of this single fixation, and (iii) this single fixation was followed by a forward saccade to the target word, Wn+1. From a total of 5205 trials, only 1263 (24 %) trials met these criteria. Therefore, we did not have enough samples per condition to do the desired 3 (temporal offset: 180 ms, 220 ms and 250 ms) X 2 (frequency: low and high) X 2 (orthography: low and high) repeated-measures ANOVA.

To increase the statistical power of the analysis, we pooled over the levels of temporal offset of the probe. Given that (i) information on the temporal offset of the probe was already taken into account to make sure that probe-onset occurred in the last 100 ms of the fixation, and (ii) we did not find any effect of temporal offset on probe discrimination, see Box 4.2, it was reasonable to pool over the levels of the temporal offset.

Consequently, we ran a 2 (frequency: low and high) X 2 (orthography: low and high) repeated-measures ANOVA on error rates, single fixation durations on Wn, saccade lengths from Wn to Wn+1, and first fixation durations on Wn+1 (i.e., target words). The average number of samples per condition per participant was 17.5 (*SEM* = 1.6) samples.

We expected to see an effect of the processing load of target words (their frequency and/or orthographic familiarity of their first trigrams) on error rates. We expected an effect of frequency on the duration of first fixation on target words to ensure that reading occurred.

Box 4.2 No effect of temporal offset in Experiment 3.

We ran a 3-way (temporal offset: 180 ms, 220 ms and 250 ms) repeated-measures ANOVA on error rates in Experiment 3, after the filtering criteria was applied. There was no effect of temporal offset (p = 0.54). The average error was 20.87 % (*SEM* = 2.9), 21.71 % (*SEM* = 2.9), and 24.73 % (*SEM* = 3.1) for temporal offsets of 180 ms, 220 ms and 250 ms, respectively. Pairwise comparison with Sidak adjustment showed no difference between different levels of temporal offset (all p-values > 0.672). The linear trend of temporal offset was not significant (p = 0.32).

4.3.2.1 Error rates

The average error rates are shown in Figure 4.2. A 2 (frequency of Wn+1: low and high) X 2 (orthographic familiarity of the first trigram in Wn+1: low and high) repeated-measures ANOVA was run on the erroneous performance on the probe. There was an effect of orthographic familiarity of the first trigram in Wn+1 ($F(1,17) = 8.285$, $p = 0.010$, $\eta^2 = 0.12$): the average error rate was 25.8 % (*SEM* = 2.3) and 18.6 % (*SEM* = 2.5) for target words beginning with low or high orthographically familiar trigrams, respectively. Therefore, the more unfamiliar the first trigram in the upcoming word was orthographically, the more attention remained at the gaze location[16]. There was no effect

[16] Drieghe, Rayner and Pollatsek (2008) showed that some parafoveal on foveal effects on fixation durations are due to mislocated fixations; that is, the eyes fixated on Wn instead of Wn+1 and, therefore, effects of the load of Wn+1 on fixation durations on Wn are reported. In this case, although Wn is fixated, it is Wn+1 that is being processed. If the observed effect of the orthographic familiarity of Wn+1 on attention, while the eyes were on Wn, in Experiment 3 was due to mislocated fixations then this effect should exist only when the distance between the launch site and Wn+1 was small (in line with an undershoot of a saccade that was planned to land on Wn+1 but landed to Wn instead). In Experiment 3, the average distance between the launch site and the beginning letter in Wn+1 was 4.4 characters (*SEM* = 0.14). To investigate any effects of this distance on error rates, we broke down trials into two groups: (i) trials in which the distance between the launch site and Wn+1 was small (smaller than 4 characters) and (ii) trials in which the distance between the launch site and Wn+1 was big (equal to or bigger than 4

of (p = 0.69) or interaction with (p = 0.38) frequency. Thus, processing of the upcoming word, before it was fixated, was not sufficiently advanced to reveal an effect of the frequency of the word on attention at the gaze location[17].

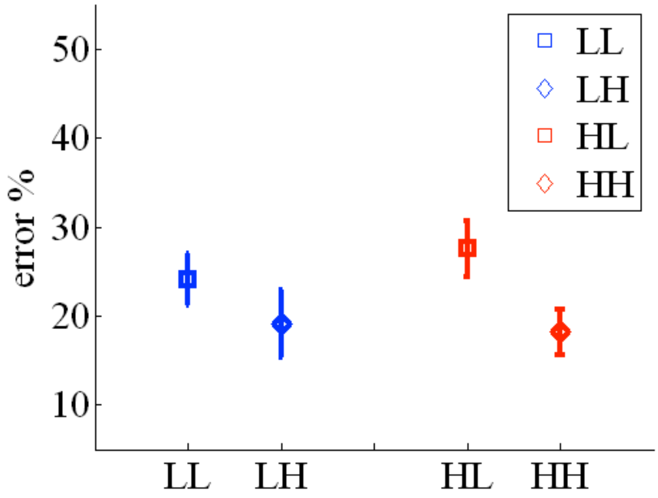

Figure 4.2. Error rates in Experiment 3. Error rates are shown during the orienting phase for central probes occurring just before the target words were fixated. Performance is broke down across low (blue lines) and high (red line) frequency target words, for where the first trigrams in target words were orthographically low familiar (squares) or high familiar (diamonds). Error bars show one standard error of the mean.

LL: low frequency target words beginning with orthographically low familiar trigrams.
LH: low frequency target words beginning with orthographically high familiar trigrams.
HL: high frequency target words beginning with orthographically low familiar trigrams.
HH: high frequency target words beginning with orthographically high familiar trigrams.

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characters). Then, we analysed only trials in which the distance was big (4 characters or bigger). A paired t-test showed an effect of orthographic familiarity of Wn+1 on error rates ($t(17) = 3.53$, p = 0.003). Thus, the observed effect of orthography on error rates was not due to mislocated fixations. We did not have sufficient statistical power to run the same analysis for the small-distance group.

[17] In those trials in which there was more than one fixation on Wn, a total of 2041 trials for eighteen participants, for probes occurring during the last 100 ms of the first fixation on Wn, there was no effect of the frequency of the target word (p = 0.418) or the orthographic familiarity of its first trigram (p = 0.69) or any interaction (p = 0.757).

4.3.2.2 Single fixation durations on Wn

The average durations of single fixations on Wn are shown in Table 4.3. The average duration was 263 ms (*SEM* = 2)[18]. A 2 (frequency: low and high) X 2 (orthography: low and high) repeated- measures ANOVA showed no effect of the frequency of Wn+1 (i.e., the target word) on single fixation durations on Wn (p = 0.23). There was an effect of the orthographic familiarity of the first trigram in Wn+1 on the durations of single fixations on Wn ($F(1,17) = 4.62$, $p = 0.046$, $\eta^2 = 0.07$): the average single fixation duration on Wn was 262 ms (*SEM* = 2) and 266 ms (*SEM* = 3) for when the first trigram in Wn+1 was orthographically unfamiliar or familiar, respectively[19]. However, the difference was too small (i.e., only 4 ms) and the statistical power was low, power = 0.52. There was no interactions (p = 0.892).

4.3.2.3 Saccade lengths from Wn to Wn+1

The average saccade lengths to the target words (i.e., from Wn to Wn+1) are shown in Table 4.4. The average saccade length from a single fixation on Wn to Wn+1 was 7.79 characters (*SEM* = 0.28). A 2 (frequency: low and high) X 2 (orthography: low and high) repeated-measures ANOVA showed no effect of frequency (p = 0.167) or orthographic familiarity (p = 0.857) of Wn+1 or interaction (p = 0.509).

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[18] The average duration of single fixations on the words that preceded the target words was 263 ms (*SEM* = 2). On the other hand, data from Experiments 1 and 2 showed that the average duration of the last fixation before the eye landed on target words was 284 ms (*SEM* = 7; see Box 4.1). One explanation for this difference could be that in the analysis provided in Box 4.1, we could not exclude trials where the eyes skipped the words that preceded the target words. In these trials, the last fixation before the eye fixated the target word was on the word that was located two words before the target words. These last fixations would be long given that fixation durations are prolonged just before a word is skipped. Thus, we over-estimated the duration of the last fixations on the words that preceded the target words.

[19] To investigate whether the observed effect of the orthographic familiarity of Wn+1 on single fixations on Wn was due to mislocated fixations (Drieghe et al., 2008; see footnote 16) we ran a 2(distance between the launch site and Wn+1: small and big) X 2 (orthographic familiarity of Wn+1: low and high) ANOVA on single fixation durations on Wn; see footnote 17. If the observed effect was due to mislocated fixation we would expect to see an interaction. One participant did not have any samples for the small distance and was excluded from the analysis. Therefore, data from 17 participants were analysed. The effect of orthographic familiarity escaped significance ($F(1, 16) = 2.22$, $p = 0.15$); nevertheless, there was no interaction ($F(1,16) = 0.12$, $p = 0.72$). Thus, we did not find any evidence that the observed parafoveal on fovea effect was due to mislocated fixations.

Average SFD on Wn		
Wn+1 frequency	Wn+1 orthography	
Low	**Low (LL)**	263
		3
	High (LH)	267
		3
High	**Low (HL)**	259
		2
	High (HH)	264
		3

Table 4.3. SFD on the words that preceded target words in Experiment 3. Average duration of single fixations (SF) on the words that preceded the target words (here, Wn) are shown for LL, LH, HL and HH target words. Standard errors of the means (SEM) are shown in italics.

4.3.2.4 First fixation duration on Wn+1 (target words)

The average duration of the first fixation on target words are shown in Table 4.5. A 2 (frequency: low and high) X 2 (orthography: low and high) repeated-measures ANOVA showed an effect of frequency of target words on the first fixation on them ($F(1,17) = 7.39$, $p = 0.014$, $\eta^2 = 0.14$): the average first fixation durations on target words was 350 ms (*SEM* = 12) and 322 ms (*SEM* = 13) for low- and high-frequency words, respectively. Thus, reading occurred. There was no effect of orthography ($p = 0.530$) and no interaction ($p = 0.268$).

Average SL from Wn to Wn+1		
Wn+1 frequency	Wn+1 orthography	
Low	**Low (LL)**	7.90
		1.63
	High (LH)	7.80
		1.11
High	**Low (HL)**	7.60
		1.20
	High (HH)	7.75
		1.29

Table 4.4. SL to target words in Experiment 3. Average saccade lengths (in characters) from single fixations on the words that preceded the target words to the target words. Mean saccade lengths (in characters) are shown for LL, LH, HL and HH target words. Standard errors of the means (SEM) are shown in italics.

Average FFD on Wn+1		
Wn+1 frequency	Wn+1 orthography	
Low	**Low (LL)**	358
		17
	High (LH)	342
		10
High	**Low (HL)**	320
		13
	High (HH)	325
		14

Table 4.5. FFD on target words in Experiment 3. Average duration of the first fixation on target words (here, Wn+1). Mean fixation durations (in ms) are shown for LL, LH, HL and HH target words. Standard errors of the means (SEM) are shown in italics.

4.4 Discussion

Analysing landing positions in a subset of the data from Experiments 1 and 2 in which the sentence belonged to the frequency/orthography stimulus set showed that the eyes landed closer to the beginning of target words when their first trigrams were orthographically less familiar (Doré-Mazars et al., 2004; Heller, 2004; Hyönä, 1995; Vonk et al., 2000; White & Liversedge, 2006). Thus, for this stimulus set, processing of the upcoming word, during preview, was sufficiently advanced to affect the eyes. In Experiment 3, we investigated whether processing of the upcoming word was sufficiently advanced to affect attention, before the word was fixated.

We lost a substantial number of trials because we only analysed trials in which there was a single fixation on the word that preceded the target word. To increase the statistical power of the analysis, we pooled over the levels of the temporal offset of the probe. This was justified because of the following reasons. First, the effect of temporal offset on error rates was not significant. Second, the information on the temporal offset of the probe was already taken into account by ensuring that the probe-onset occurred within the last 100 ms of the fixation.

In accepted trials, the duration of the first fixation on target words was longer for words that were low rather than high in frequency. This was in spite of the fact that the probe occurred before the target word was fixated. An effect of frequency on the duration of first fixations on target words confirmed that reading occurred (Rayner & Raney, 1996).

4.4.1 Attention

The more demanding the first trigram in the target word was orthographically the less attention remained at the gaze location, during the last 100 ms before the saccade to the target word. This is, to the best of our knowledge, the first report of an effect of the load of the to-be-fixated location on attention at the gaze location.

We did not find any effect of the frequency of the target word on attention at the gaze location. It is possible that, shortly before the target word was fixated, its processing had reached those levels that correspond to its frequency but was not sufficiently advanced/strong to reveal an effect of frequency on attention at the gaze location. Our results showed that, before a word is fixated, its processing affects attention as well as the programming of the upcoming saccade.

4.4.2 Eye-movement behaviours

The frequency of target words affected the duration of first fixations on them but did not affect (i) the landing positions on them or (ii) the duration of single fixations on the words that preceded them. This suggests that processing of target words, before they were fixated, either (i) did not reach those levels that correspond to their frequencies or (ii) did reach those levels but the processing was not sufficiently early/strong to reveal any effects of frequency on the metrics or the timing of the upcoming saccade. This is in line with no effect of the frequency of the target words on attention before they were fixated.

The duration of single fixations on the words that preceded target words was shorter when the first trigrams in target words were less familiar. Some studies have found an opposite effect of orthographic informativeness, but not familiarity, of the initial letters of a word on how long the eyes fixate the previous word (Kennedy & Pynte, 2005). Although, in our study, the statistical power of this effect was low and the size of the effects was small, the direction of the effect was in line with the effect of the orthographic familiarity of first trigrams in target words on attention at the gaze location. Our interpretation is that, shortly before a saccade, when the orthographic familiarity of the first trigram in the upcoming word was low, as opposed to when it was high, less attention remained at the gaze location because there was more demand for attention at the to-be-fixated location. Consequently, the execution of the saccade to the to-be-fixated word was facilitated, resulting in a shorter fixation.

In sum, our results suggested that both attentional mechanisms and oculomotor mechanisms are affected by the moment-to-moment load of the word that is being processed, which is not necessarily the fixated word. The results are important in terms of bridging between the attentional, the oculomotor, and the word-processing literature.

4.5. Next Experiment

We showed that, for the task of reading sentences, the load of the word that is being processed affects attention: (i) shortly before a word is fixated, the orthographic familiarity of its first trigram affects attention; (ii) just after it is fixated, its frequency affects attention (results from Experiments 1, 2 and 3). We reasoned that participants had valid preview of the word before fixating on it resulting in the effect of orthography on attention, before the word is fixated, and frequency on attention, after the word is fixated.

It has been suggested that the preview benefit depends on the size of the perceptual span (McConkie & Rayner, 1975). The span is narrower when the task is harder (Häikiö et al, 2009; Inhoff et al., 1989). This raises the question whether there would still be an effect of the frequency of the target word on the focus of attention if the reading task became harder, resulting a smaller perceptual span and, therefore, less preview.

In Experiment 4, described in chapter 5, we changed the reading task from ‘reading sentences for comprehension’ to ‘reading strings of random words for identification’. We expected that, if the manipulation in the reading task results in a smaller preview benefit, then attention should be affected less, if at all, by the frequency of the fixated word, early in a fixation. In Experiment 5, described in chapter 6, we denied valid preview of words. We expected that there should be no effect of the frequency of the fixated word on attention when no preview is obtained, early in a fixation (i.e., at temporal offsets of 10 and 40 ms).

Chapter 5

Effects of the load of the fixated word on the focus of attention when reading strings of words

5.1 Introduction

In Experiments 1 and 2, early in a fixation and 6 characters from the gaze location, the amplitude of attention was smaller when the fixated word was low rather than high in frequency when reading sentences for comprehension. We concluded that attention was focused on the gaze location more when the fixated word was low rather than high in frequency, during the engagement phase, in reading sentences (Ghahghaei et al., 2013). In Experiment 4, we addressed whether this effect of frequency on the focus of attention remains when the reading task is more demanding, for example, when the task is to read strings of random words as opposed to sentences.

For the task of reading sentences, we reasoned that the effect of frequency on the focus of attention, during the engagement phase, was because participants obtained sufficient preview of the words. Processing of the word is integrated across the saccade to the word (e.g., Inhoff et al., 2000; Rayner & Clifton, 2009). In other words, preview affects the level of processing of the word over the course of a fixation. Thus, given preview, early in a fixation, processing of words was sufficiently advanced to reveal an effect of frequency on attention in reading sentences.

Preview is modulated by the size of the perceptual span: less preview is obtained when the span is narrower (Henderson & Ferreira, 1990). The size of the span is in turn modulated by the reading task: the span is narrower when the reading task is harder (Häikiö et al, 2009; Inhoff et al., 1989). Therefore, when the reading task becomes harder, the size of the span and, presumably, the amount of preview reduces.

In Experiment 4, we changed the reading task from ‘reading sentences’ to ‘reading strings of random words‘. The task of reading strings of words is more demanding than the task of reading sentences. This is because, for the task of reading sentences, processing of words can benefit from the context. In reading strings of random words, on the other hand, there is no context to benefit from. In addition, in a string of words (nouns), compared to a sentence of the same length in characters, there are more words (nouns) to be processed. This is because there was no articles or function words in our stimulus set for this study; this can delay or slow down the processing of target words given that there are preceded by more words (as indexed by longer fixations on them; e.g., Kuperman, Dambacher, Nuthmann, & Kliegl, 2010). Consequently, the speed of reading is slower for the task of reading strings of words than sentences (Sass, Legge, & Lee, 2006). All the above suggest that the task of reading strings of words is harder than the task of reading sentences. Consequently, we expected a narrower perceptual span (Häikiö et al, 2009; Inhoff et al., 1989) resulting less preview of the upcoming word, for the task of reading strings of words than sentences. Thus, it is possible that, when reading strings of words, early in a fixation processing of the fixated word is not sufficiently advanced to reveal an effect of frequency on attention.

In Experiment 4, we used a frequency/orthography/words stimulus set (see section 5.3.2). Target words in the frequency/orthography/words stimulus set were the same as target words in the frequency/orthography stimulus set which was used in Experiment 3. As a result, the frequency of target words and the orthographic familiarities of their first trigrams were orthogonally manipulated to be high or low. A target word was embedded in a string of random words in each trial. We probed attention 6 characters to the left or right of the gaze location, early during the first fixation (i.e., at temporal offsets of 10 or 40 ms) on the target word (Wn) in each string of words. Thus, Experiment 4 was a 2 (frequency) X 2 (orthographic familiarity of the first trigram) X 2 (spatial offset) X 2 (temporal offset) design. For the primary task, participants read one string of random words at a time. In 25 % of the trials, after the participant had read the string, an identification question appeared; the participant was asked to decide which of two words had been presented in the string of words that they had just read (Figure 5.1). The secondary task was as in Experiments 1, 2 and 3; namely, unspeeded discrimination of the orientation of the probe.

We now sharpen our predictions in terms of attention. To address whether, early in a fixation, the difficulty of the reading task modulates attention, we compared the results of those trials in which peripheral probes occurred with a temporal offset of 40 ms in Experiment 1 (where participants read sentences) with those trials in which peripheral probes occurred with a temporal offset of 40 ms in Experiment 4 (where participants read strings of words). The perceptual span is narrower for harder tasks (e.g., Häikiö et al., 2009; Inhoff et al., 1989). It is, therefore, possible that attention was more focused on the gaze location, during the engagement phase, for reading words than sentences. This being the case, we would expect an effect of reading task on error rates; specifically, would expect higher error rates on discriminating peripheral probes occurring with a temporal offset of 40 ms for the task of reading strings of words than sentences. On the other hand, it is possible that only later in a fixation (i.e., at temporal offsets later than 40 ms) the span was significantly narrower for the task of reading strings of words than sentences. This being the case, we would not expect an effect of task on error rates.

The perceptual span is known to be asymmetric around the gaze for different reading tasks (e.g., Häikiö et al., 2009; Inhoff et al., 1989). Our results in Experiments 1 and 2 showed that attention was asymmetric around the gaze and that it defocused over time from the beginning of a fixation for the task of reading sentences (Ghahghaei et al., 2013). We proposed that attention would be asymmetric on the gaze and would defocus over time for the task of reading strings of words as well. Thus, we expected better accuracy for discrimination of the orientation of (i) right than left probes and (ii) probes occurring 40 than 10 ms into a fixation.

For the task of reading sentences, there was an effect of the frequency of the target word on the focus of attention, early in a fixation (Experiments 1 and 2); this effect was in the expected direction 10 ms into the fixation and was significant on the left side of the gaze location by 40 ms into the fixation. For the task of reading strings of words, it was possible that the preview that was obtained from the target word was insufficient to reveal any effects of frequency on the focus of attention, early in a fixation (i.e., at temporal offsets of 10 and 40 ms). It was also possible that frequency would affect attention but that the effect would not be as strong as the effect in reading sentences. Either of these possibilities being the case, one would expect an interaction between frequency and the reading task. On the other hand, it was possible that the preview benefit was sufficient to reveal an effect of frequency on the focus of attention and that this effect was no weaker for the task of reading strings of words than the task of reading sentences; this being the case, one would not expect an interaction between frequency and the reading task.

For the task of reading sentences, 40 ms into the fixation, the effect of frequency was only observed for left probes. Right probes were less sensitive than left probes to the effects of the load of the fixated word, presumably because, by 40 ms into a fixation right probes occurred inside the perceptual span. For the task of reading strings of words, which presumably has a narrower perceptual span, we expected that both left and right probes would be sensitive to the effect of frequency, early in a fixation. Hence, we expected that any effects of frequency on the focus of attention would be revealed for both left and right probes. In other words, we did not expect an interaction between spatial offset and word frequency for the task of reading strings of words.

In the frequency/orthography/words stimulus set the orthographic familiarity of the first trigram in target words was manipulated to be high or low. Therefore, for the first time we could also see whether there is any effect of this manipulation on the focus of attention around the gaze location early in a fixation. In Experiment 3 we showed that processing of words during preview is sufficiently advanced to reveal an effect of the orthographic familiarity of the first trigram in a word on attention before the word is fixated when reading sentences. If preview is smaller in reading strings of words, as opposed to sentences, then it is possible that word processing is delayed and the orthographic familiarity of the word, but not its frequency, affects attention early in a fixation. Thus, there could be an effect of orthographic familiarity of the first trigram and less effect of frequency, if any, on attention.

We now sharpen our predictions in terms of eye movements. We expected that the speed of reading would be considerably smaller for the task of reading strings of words than sentences. In other words, we expected longer fixation durations (e.g., Kuperman, Dambacher, Nuthmann, & Kliegl, 2010) and shorter saccades (Ashby et al., 2005; Rayner, 1998; Kaakinen & Hyönä, 2010) for reading strings of words than sentences. The eyes were expected to land closer to the beginning of words when reading strings of words than sentences, given that the former was a harder task (Kaakinen & Hyönä, 2010). In addition, the eyes were expected to land closer to the beginning of words when the words' first trigrams were orthographically less familiar (e.g., Vonk et al., 2000). An effect of orthographic familiarity on landing positions would confirm that the word was previewed before being fixated.

For the task of reading sentences, peripheral probes with temporal offsets of 10 ms (Experiment 2) and 40 ms (Experiment 1) (i) prolonged fixations and (ii) shortened saccades equally. Therefore, we did not expect an effect of temporal offset on first fixation durations or saccade lengths for reading strings of words. In a similar way, we expected that fixations would be prolonged more for left than right probes.

For the task of reading sentences, saccades were shortened by right probes more than left probes because right probes occurred between the gaze location and the intended saccadic target had the probe not occurred. For the task of reading strings of words, we did not expect that a right probe would shorten the upcoming saccade more than a left probe. This is because saccades are expected to be shorter for the task of reading strings of words than sentences. Thus, we did not expect an effect of the spatial offset of the probe on saccade lengths.

We also did not expect an effect of frequency on saccade lengths. This is because for peripheral probes occurring 10 or 40 ms into a fixation, the effect of frequency on saccade lengths was not preserved when reading sentences (sections 2.3.1.3 and 3.3.2.6). Nevertheless, we expected an effect of frequency on the duration of first fixation on target words to ensure that reading occurred (Rayner & Raney, 1996). We expected no effect of the orthographic familiarity of the first trigram in target words on the duration of first fixations on them. This is because we did not find such an effect for the task of reading sentences (results of Experiment 3).

5.2 Method

5.2.1. Participants

Fifteen native mono-lingual English-speakers participated in Experiment 4 (10 female; all students in San Francisco). They were all between 18 and 30 years old. They received money for their participation.

5.2.2 Apparatus

Same as in Experiment 3 for participants in San Francisco.

5.2.3 Stimuli

A new stimulus set, the *frequency/orthography/words* stimulus set, was made. The frequency/orthography/words stimulus set was based on the frequency/orthography stimulus set that was used in Experiment 3. For each sentence in the frequency/orthography stimulus set we made a corresponding string of words in the frequency/orthography/words stimulus set. The word units were random words (not verbs, adverbs or articles) from 5 to 8 characters in length. The words were not predictable from the previous words in the string. There was no repetition of the words in a string of words. The lengths of each string of words in the frequency/orthography/words stimulus set was roughly the same as the lengths of its corresponding sentence in the frequency/orthography stimulus set. Each string of words had the same target word as in its corresponding sentence. The distance (in characters) between a target word and the beginning of the string of words that contained it was roughly the same as the distance in its corresponding sentence. The words that preceded the target words in each string of words in the frequency/orthography/words stimulus set was chosen from the top 500 high-frequency words [20] excluding those words that were already used for a high-frequency target word in the frequency/orthography stimulus set. As in the frequency/orthography stimulus set, there were four groups in the frequency/orthography/words stimulus set; for each group the frequency of target words and the orthographic familiarities of their first trigrams were either low or high. In the following, one sample of a string of words from each group is provided. Note that in each string of words, the target word (i.e., Wn) is italicised only for the presentation purpose.

(i) The LL group in which the target word was a low-frequency word and the first trigram in the target word was orthographically low familiar.

`Feeling waiter quarter insurer` *`tundra`* `needs counter infant.`

(ii) The LH group in which the target word wass a low-frequency word and the first trigram in the target word was orthographically high familiar.

`North biases dealer sweets` *`mishap`* `handle music mileage wreck.`

[20] We used this website to choose Wn-1: http://ucrel.lancs.ac.uk/bncfreq/lists/5_1_all_rank_noun.txt

(iii) The HL group in which the target word was a high-frequency word and the first trigram in the target word was orthographically low familiar.

`Ships customs hints expert` *`guide`* `summit excuse legend friend.`

(iv) The HH group in which the target word was a high-frequency word and the first trigram in the target word was orthographically high familiar.

`Human licence queen trouble` *`mission`* `debate signal folder penny.`

5.2.4 Design

Participants read strings of words from the frequency/orthography/words stimulus set. Each string of words contained a target word, Wn. Target word was either low or high in frequency and the orthographic familiarity of its first trigrams was either high or low. The probe occurred with a temporal offset 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, Experiment 4 was a 2 (frequency of Wn) X 2(orthographic familiarity of the first trigram in Wn) X 2(spatial offset) X 2(temporal offset) design.

For each level of the load of the target word (i.e., the frequency of the target word and the orthographic familiarity of its first trigram), there were 88 strings of words. Consequently, for each level of the experimental design, there were 22 strings of words. For each participant, a list of 352 strings of words was made with a randomized order of the experimental conditions. Each participant was presented with a different list. Experiment 4 was run in three sessions, preferably in two separate days. If separate days were not possible, participants had at least a one hour break between the sessions.

5.2.5 Procedure

For the primary task, each participant read strings of words; see Figures 5.1. One string of words was presented on the screen at a time. Strings of words were left aligned. Participants were asked to read the words in silence. In 25% of the trials, participants answered an *identification* question *after* they read the string of words; so they were asked whether or not a specific word was presented in the string of words they just read. The word to be identified was always chosen from the first or the last two words in the string, but participants were not informed about this. The target word was never within the first or the last two words; therefore, the word to be identified was never the target word. Participants were frequently reminded to read with their normal speed of reading; that is, neither very slow and nor very fast.

Gaze-contingent probes occurred when the eye landed on Wn in each string of words. In Experiment 4, similar to Experiments 1 and 2, Wn was ‘the target word’ given that we looked at the load of the fixated word on attention. The secondary task was to discriminate the orientation of the probe after they read the string of words. Participants were informed that the probe only occurred in the periphery and not at the gaze location.

In the beginning of the first session, participants received a long block of practice trials where, for the primary task, they read two sets of ten and thirty *sentences* for comprehension (as in Experiments 1-3). All the target words in these sentences were high in frequency. The probe occurred with temporal offset of 40 ms and spatial offset of -6 or +6 characters. Participants received verbal feedback on their performance on the probe. We initially chose the luminance of the probe for each participant based on the average luminance from the previous participants who were in the same range of age. To avoid the ceiling or the floor effect, the probe luminance was adjusted for each participant during the practice trial to maintain about 75% accuracy on the probe.

The luminance of the probe was adjusted based on the performance on the probe while reading sentences rather than strings of words. The reason we did this is that we wanted overall probe discrimination in Experiments 4 (in which participants read strings of words) to be comparable with overall probe discrimination in Experiments 1 and 2 in which participants read sentences, so that we could look at the effects of the reading task on the focus of attention.

After the luminance of the probe was adjusted, the participant received another block of practice in which for the primary task she/he read a set of twenty *strings of words* followed by an identification question.

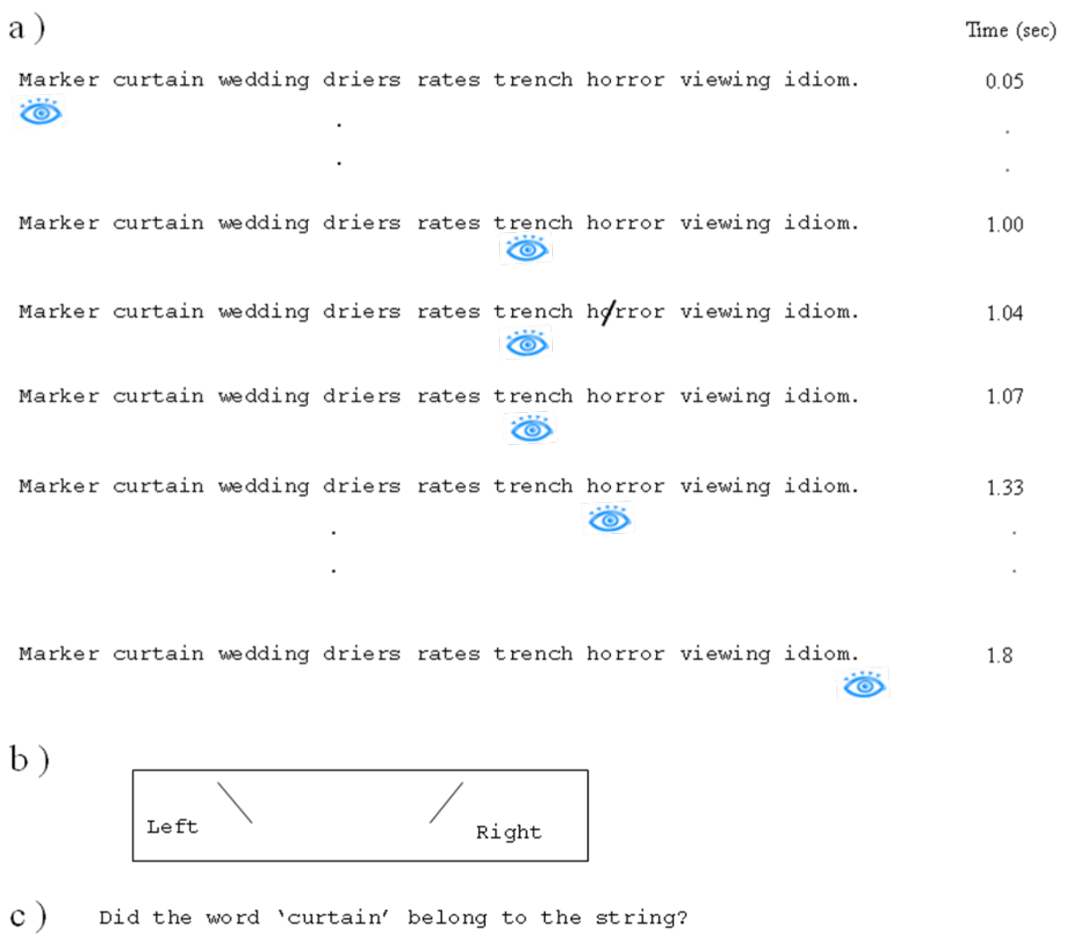

Figure 5.1. A schematic representation of one trial in Experiment 4. One string of words at a time was presented on the screen (a). Participant read the string in silence. There was a target word in each sentence, here the word 'trench'. The frequency of the target word was either high or low; here 'trench is a low-frequency word. The orthographic familiarity of the first trigram in the target word was either high or low; here 'tre' is high in orthographic familiarity. After some temporal offsets (here temporal offsets of 40 ms) from the beginning of the first fixation on the target word, the probe occurred 6 characters from fixation, here on the right. The probe was only presented for 30 ms. Participants were instructed to (i) try to not be distracted by the probe and (ii) continue reading. Participants were instructed to read each string no more than one time. After the string disappeared, another screen appeared and asked about the orientation of the probe (b). After the response to the probe was made, in 25 % of the trials, another screen appeared and participants were to identify whether a specific word was presented in the string(c).

5.3 Results

For the analysis, participants who had more than 40% or less than 10% error on performance on the probe were excluded. As a result, data from 13 participants (9 female) was analysed. Trials were included if (i) the target word, Wn, was fixated (ii) for at least 100 ms, and (iii) this fixation was followed by a forward saccade – the filtering criteria. From a total of 4343 trials, 3691 trials were included (85 %) due to the filtering criteria. Experiment 4 was a 2 (frequency) X 2 (orthography) X 2 (spatial offset) X 2 (temporal offset) design. The average number of accepted trials per condition per participant was 17.76 (*SEM* = 0.58) samples.

We looked at the effects of the reading task (i.e., reading strings of words versus sentences) by analysing peripheral probes occurring with a temporal offset of 40 ms in Experiments 1 and 4. We pooled over the levels of the orthographic familiarity of first trigrams for this analysis given that in Experiment 1, the task of reading sentences, we did not manipulate the orthographic familiarity of first trigrams in target words.

We chose the first thirteen participants in Experiment 1 who had more samples from the frequency/orthography stimulus set for the temporal offset of 40 ms. We only included those trials in Experiment 1 where the sentence belonged to the frequency/orthography stimulus set. We looked at the effect of the reading task on the speed of reading and the landing positions on target words for these participants from Experiment 1 and those who participated in Experiment 4.

Then, we analysed data from *Experiment 4* by running a 2 (frequency: low and high) X 2 (orthography: low and high) X 2 (spatial offset: -6 and +6 characters) X 2 (temporal offset: 10 ms and 40 ms) repeated-measures ANOVA on error rates (section 5.3.2), first fixation durations (section 5.3.3) and saccade lengths from these fixations (section 5.3.4). For each of these DVs, we also looked at the effects of the reading task (the task of reading sentences versus reading strings of words) for when peripheral probes occurred with temporal offset of 40 ms.

5.3.1 The speed of reading

The speed of reading in each trial was calculated as ‘the distance from the beginning of the line of text in characters to the beginning of the target word’, divided by ‘the amount of time elapsed from the beginning of the trial until the participant’s eye reached the first character in the target word for the first time’. The average speed of reading was 22.25 (*SEM* = 0.85) characters per second, for the task of reading sentences

(Experiment 1), and 16.94 (*SEM* = 1.21) characters per second, for the task of reading strings of words (Experiment 4). Hence, reading strings of words was more demanding than reading sentences. This in turn supports that the perceptual span was narrower for the task of reading strings of words than sentences.

5.3.2 Landing positions on target words (Wn)

In chapter 4, we showed that for the task of reading sentences, the orthographic familiarities of the first trigrams in target words affect the landing positions on them. Here, we investigate if the same stands for the task of reading strings of words. We did not have as many participants in Experiment 4 as we did in Experiments 1 and 2. Consequently, the statistical power of the analysis was too low to do a 2 (orthographic familiarity of the first trigram) X 2 (frequency) X 4 (launch site distance) ANOVA on landing position. To increase the statistical power, we pooled over the levels of the frequency of target words. This was justified given that, to the best of our knowledge, there is no report of an effect of frequency on landing position and we did not find an effect of frequency on landing position for the task of reading sentences.

We ran a 4 (launch site distance: 4, 5, 6 and 7 characters) X 2 (orthographic familiarity of first trigrams in target words: low and high) repeated-measures ANOVA on the landing position on target words. There were on average 20.39 (*SEM* = 1.81) samples per condition per participant.

Average landing positions on target words, Wn, are shown in Table 5.1. The average landing position was 1.35 (*SEM* = 0.18) characters which was smaller than the average landing position in reading sentences (mean = 2.15, *SEM* = 0.12; results for data from Experiments 1 and 2 presented in chapter 4). This further supports that reading strings of words was a harder task than reading sentences and the landing positions shifted closer to the beginning of the words.

Mauchly’s test of sphericity was significant for launch site distance ($p = 0.001$). Therefore, we reported the corrected (lower-bound) *p*-value for launch site. There was an effect of the distance of the launch site ($F(3,36) = 18.06$, $p = 0.001$, $\eta^2 = 0.53$): the average landing position was 1.96 (*SEM* = 0.27), 1.52 (*SEM* = 0.20), 1.12 (*SEM* = 0.17) and 0.82 (*SEM* = 0.17) characters when the launch sites was 4, 5, 6 and 7 characters away from the first letter in the fixated word, respectively. Pairwise comparison with Bonferroni correction showed marginal difference between launch site distances of 6 and 7 characters ($p = 0.060$) and significant difference between all other levels of launch site distances ($p < 0.04$). Therefore, similar to the results for the task of reading sentences, landing positions shifted towards the beginning of the words the further the launch site.

Average landing position on target words, Wn , in Experiment 4				
	Launch site distance to Wn			
	4	**5**	**6**	**7**
Orthographic familiarity of the first trigram in Wn				
Low	1.82	1.45	1.09	0.83
	0.27	*0.19*	*0.15*	*0.17*
High	2.10	1.58	1.15	0.82
	0.28	*0.21*	*0.20*	*0.20*

Table 5.1. LP on target words in Experiments 4. Average landing positions (in characters) on target words are shown for where the first trigrams in target words were orthographically low- or high-familiar. Performance is shown across launch site distances of 4, 5, 6 or 7 characters. Standard errors of the means (*SEM*) are shown in italics.

There was an effect of the orthographic familiarities of the first trigrams in target words ($F(1,12) = 6.10$, $p = 0.024$, $\eta^2 = 0.01$): the average landing position was 1.30 (*SEM* = 0.18) and 1.42 (*SEM* = 0.19) characters for target words beginning with low and high orthographically familiar trigrams, respectively. Therefore, similar to the task of reading sentences, landing positions shifted towards the beginning of the words by a decrease in the orthographic familiarity of their first trigrams. Thus, preview of the words was sufficient to affect the landing positions on them. There was no interaction ($p > 0.05$).

5.3.3 Error rates

The results on probe discrimination in Experiment 4 are provided in section 5.3.3.1. Then, the results of the effect of the reading task on probe discrimination are provided in section 5.3.3.2 (data from Experiments 1 and 4).

5.3.3.1 Error rates in Experiment 4

Figure 5.2. shows the error rates in Experiment 4. A 2 (frequency: low and high) X 2 (orthography: low and high) X 2 (spatial offset: -6 and +6 characters) X 2

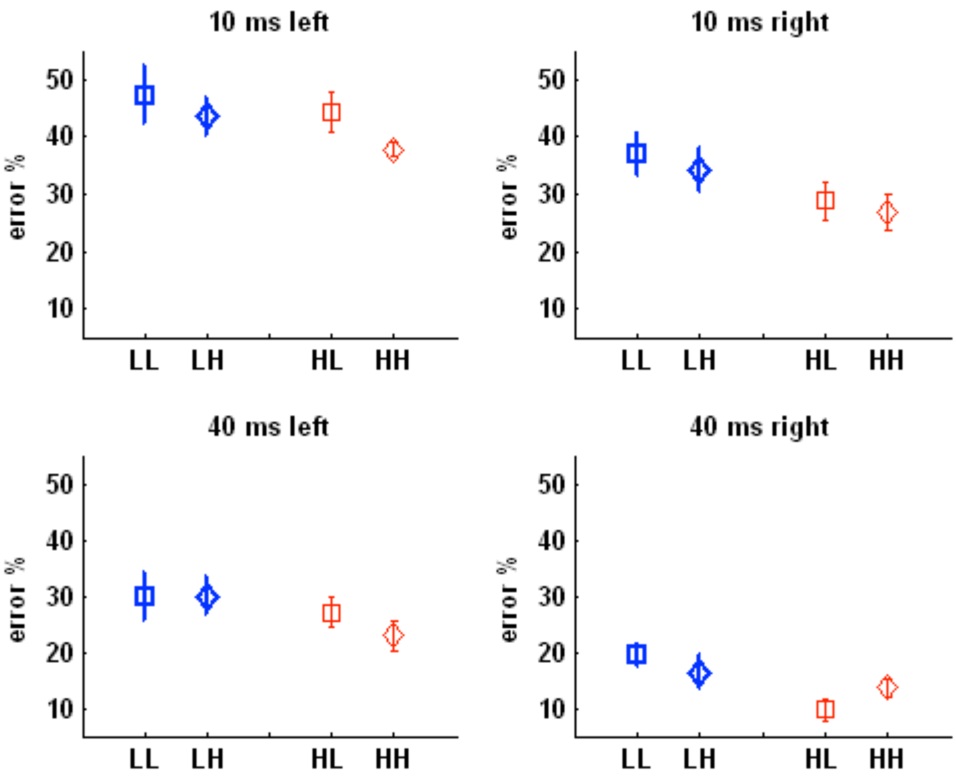

Figure 5.2. Error rates in Experiment 4. Performance on the probe, for the task of reading strings of words, is shown for left (left panels) and right (right panels) probes with temporal offsets of 10 ms (top panels) or 40 ms (bottom panels). Performance is broke down across low (blue lines) and high (red line) frequency target words, for where the first trigram in target words was orthographically low familiar (squares) or high familiar (diamonds). Error bars show one standard error of the mean.

LL: low frequency target words beginning with orthographically low familiar trigrams

LH: low frequency target words beginning with orthographically high familiar trigrams

HL: high frequency target words beginning with orthographically low familiar trigrams

HH: high frequency target words beginning with orthographically high familiar trigrams

(temporal offset: 10 ms and 40 ms) repeated-measures ANOVA was run on error rates. There was an effect of the spatial offset of the probe ($F(1,12) = 40.05$, $p = 0.001$, η^2 =

0.17): the average error rate was 35 % (*SEM* = 1.3) for left and 23.7% (*SEM* = 1.4) for right probes. Therefore, attention was skewed towards the right. There was an effect of the temporal offset of the probe ($F(1,12) = 156.27$, $p = 0.001$, $\eta^2 = 0.30$): the average error rate was 37.45 % (*SEM* = 1.4) and 21.11 % (*SEM* = 1.3) for temporal offsets of 10 and 40 ms, respectively. Therefore, attention defocused over time. There was an effect of word frequency ($F(1,12) = 16.21$, $p = 0.002$, $\eta^2 = 0.04$): the average error rate was 32.17 % (*SEM* = 1.68) and 26.34 % (*SEM* = 0.98) for low- and high-frequency words, respectively. Thus, attention was focused on the gaze more for low- than high-frequency words. There was a marginal effect of orthographic familiarity of first trigrams but the statistical power was low ($F(1,12) = 3.77$, $p = 0.076$, statistical power = 0.432): average error rate was 30.38 % (*SEM* = 1.32) for low and 28.14% (*SEM* = 1.25) for highly familiar words. There were no other effects or interactions (all *p*-values > 0.05).

5.3.3.2 The effects of the reading task on error rates

We looked at the effects of the reading task (i.e., reading strings of words versus sentences) on the focus of attention 40 ms into a fixation. We pooled over the levels of the orthographic familiarity of first trigrams in target words because the task of reading sentences, we did not manipulate the orthographic familiarity of first trigrams in target words, in Experiment 1. Furthermore, in Experiment 4, the task of reading strings words, (i) there was no interaction between the frequency of the fixated word and the orthographic familiarity of its first trigram on the focus of attention, and (ii) the effect of orthographic familiarity was marginal and had a low statistical power.

A 2 (reading task: reading sentences versus strings of words) X 2 (spatial offset: left and right) X 2 (frequency: low and high) mixed-effects ANOVA was run on error rates with primary task as a between-subject variable.

There was no effect of reading task ($F(1,24) = 2.35$, $p = 0.138$): the average error rate was 27.31 % (*SEM* = 2.7) and 22.11 % (*SEM* = 1.3) for that task of reading sentences and strings of words, respectively. There was an effect of spatial offset ($F(1,24) = 20.85$, $p = 0.001$, $\eta^2 = 0.18$): the average error rate was 30.11% (*SEM* = 2.24) and 18.79 % (*SEM* = 2.21) for left and right probes, respectively. There was an effect of frequency ($F(1,24) = 18.94$, $p = 0.001$): the average error rate was 29.03 (*SEM* = 2.57) and 19.86 % (*SEM* = 1.70) for low- and high-frequency words, respectively.

There was an interaction between reading task and frequency ($F(1,24) = 4.55$, $p = 0.043$, statistical power = 0.53) but the statistical power was low.

To further investigate this interaction, we looked at the effect of the reading task on the *difference* between probe discrimination for low-frequency and high-frequency words (pooled over levels of spatial offset). A one-way ANOVA showed a marginal effect of reading task on the difference between performances on the probe for when low-frequency or high-frequency words were fixated ($F(1, 24) = 3.64$, $p = 0.068$): the difference on probe discrimination was 13 % (*SEM* = 4) and 5 % (*SEM* = 7) for the task of reading sentences and the task of string of words, respectively. The results suggested that, 40 ms into a fixation, participants' performance on the probe improved with an increase in the frequency of the fixated word and this improvement was better when participants' task was to read sentences than strings of words. In other way of saying, the effect of frequency on the focus of attention was marginally stronger for the task of reading sentences than reading strings of words.

One might expect an interaction between reading task, frequency and spatial offset. That is because, 40 ms into a fixation, the effect of frequency was observed for both left and right probes in Experiment 4 (the task of reading strings of words), but only for left probes in Experiment 1 (the task of reading sentences). Such an interaction was not significant ($p = 0.27$; statistical power = 0.19). The statistical power of the analysis was too low for a three-way interaction given that (i) only 13 participants from Experiment 1 were included and (ii) from these participants, only a subset of trials that belonged to the frequency/orthography stimulus set were included.

Nevertheless, for these thirteen participants from Experiment 1 and for this subset of trials, the effect of frequency was significant ($F(1, 12) = 9.82$, $p = 0.009$) for left probes: the average error rate was 41.61 % (*SEM* = 5.12) and 22.91 % (*SEM* = 5.09) for low- and high-frequency words respectively. On the other hand, the effect of frequency was not significant for right probes ($F(1,12) = 1.45$, $p = 0.25$): the average error rate was 26.86 % (*SEM* = 4.48) and 18.19 % (*SEM* =3.67) for low- and high-frequency words, respectively. Therefore, the effect of frequency was only significant for left probes with a temporal offset of 40 ms for the task of reading sentences. This is in line with the results in Experiment 1 (i.e., the results for 22 participants) where, 40 ms into a fixation, the effect of frequency was only significant for left probes .

5.3.4 First fixation durations on target words (Wn)

First, the results on fixation durations in Experiment 4 are provided in section 5.3.4.1. Then, the results of the effect of the reading task on fixation durations are provided in section 5.3.4.2 (data from Experiments 1 and 4).

5.3.4.1 First fixation durations on target words in Experiment 4

Average durations of the first fixation on target words, Wn, are shown in Table 5.2. A 2 (frequency: low and high) X 2 (orthography: low and high) X 2 (spatial offset: -6 and +6 characters) X 2 (temporal offset: 10 ms and 40 ms) repeated-measures ANOVA was run on the duration of first fixation on target words.

Average FFD on target words, Wn (ms)					
Spatial offset (characters)		**-6 (left)**		**+6 (right)**	
temporal offset (ms)		**10**	**40**	**10**	**40**
Wn frequency	Wn orthography				
Low	**Low (LL)**	462	503	390	384
		28	*30*	*16*	*23*
	High (LH)	476	494	391	405
		30	*31*	*19*	*27*
High	**Low (HL)**	456	473	371	395
		36	*33*	*20*	*23*
	High (HH)	439	492	385	387
		26	*34*	*18*	*19*

Table 5.2. FFD on target words in Experiment 4. Mean fixation durations (in ms) are shown for left and right probes with a temporal offset of 10 ms or 40 ms. Performance is broke down for LL, LH, HL and HH target words. Standard errors of the means (SEM) are shown in italics.

There was an effect of frequency on the duration of first fixation on target words (F(1,12) = 8.58, p = 0.013, η^2 = 0.003): the average first fixation duration on target words was 438 ms (*SEM* = 20) and 426 ms (*SEM* = 21) for low- and high-frequency words, respectively. An effect of frequency on the duration of first fixations confirmed that reading occurred.

There was an effect of the spatial offset of the probe (F(1,12) = 24.56, p = 0.001, η^2 = 0.12): the average duration of the first fixation on target words was 474 ms (*SEM* = 26) for left and 389 ms (*SEM* = 17) for right probes. Therefore, similar to the results for the task of reading sentences, left probes prolonged the fixations more than right probes. There was an effect of the temporal offset of the probe (F(1,12) = 11.80, p = 0.005, η^2 = 0.06). The average duration of the first fixation was 422 ms (*SEM* = 19) and 441 ms (*SEM* = 21) ms for temporal offsets of 10 ms and 40 ms, respectively. Therefore, probes with a temporal offset of 40 ms prolonged the fixations more than those with a temporal offset of 10 ms. There was an interaction between the spatial and temporal offsets of the probe (F(1,14) = 11.56, p = 0.004, η^2 = 0.01). Breaking down this interaction for left and right probes, there was an effect of temporal offset for left probes (F(1,12) = 15.09, p = 0.002, η^2 = 0.16): the average first fixation duration on target words was 458 ms (*SEM* = 25) and 490 ms (*SEM* = 28) for temporal offsets of 10 ms and 40 ms, respectively. There was no effect of temporal offset for right probes (F(1,12) = 1.12, p = 0.311). Therefore, the effect of temporal offset was only revealed for left probes. There was no other reliable effects or interaction ($p > 0.05$).

5.3.4.2 The effects of the reading task on fixation durations

Similar to the analysis on the effects of the reading task on error rates, we ran a 2 (reading task: reading sentences versus strings of words) X 2 (spatial offset: left and right) X 2 (frequency: low and high) mixed-effects ANOVA on first fixation durations with reading task as a between-subject variable (on those trials in which the probe occurred with a temporal offset of 40 ms).

As one would expect, the effects of frequency (p = 0.02) and spatial offset (p = 0.001) were significant. The effect of reading task was significant (F(1,24) = 19.49, p = 0.001): the average duration of the first fixation on target words were 322 ms (*SEM* =

18) and 437 ms (SEM = 20) for the tasks of reading sentences and strings of words, respectively. There was no other reliable effects or interactions ($p > 0.05$).

5.3.5 Saccade lengths

First, the results on saccade lengths in Experiment 4 are provided in section 5.3.5.1. Then, the results of the effect of the reading task on saccade lengths are provided in section 5.3.5.2 (data from Experiments 1 and 4).

5.3.5.1 Saccade lengths in Experiment 4

Average saccade lengths are shown in Table 5.3. A 2 (frequency: low and high) X 2 (orthography: low and high) X 2 (spatial offset: -6 and +6 characters) X 2 (temporal offset: 10 ms and 40 ms) repeated-measures ANOVA was run on saccade lengths. There were no reliable effects or interactions; all *p*-values > 0.05. The average saccade length from the first fixation on target words was 5.11 characters (*SEM* = 0.39).

Average saccade length (characters)					
Spatial offset (characters)		**-6 (left)**		**+6 (right)**	
temporal offset (ms)		**10**	**40**	**10**	**40**
Wn frequency	Wn orthography				
Low	**Low (LL)**	5.70	5.38	4.91	5.09
		0.47	*0.45*	*0.34*	*0.37*
	High (LH)	5.08	5.05	4.78	5.07
		0.38	*0.41*	*0.34*	*0.34*
High	**Low (HL)**	4.96	5.88	4.90	5.09
		0.34	*0.65*	*0.29*	*0.35*
	High (HH)	4.98	4.92	4.81	5.04
		0.34	*0.38*	*0.34*	*0.31*

Table 5.3. SL in Experiment 4. Mean saccade lengths (in characters) are shown for left and right probes with a temporal offset of 10 ms or 40 ms. Performance is broke down for LL, LH, HL and HH target words. Standard errors of the means (SEM) are shown in italics.

5.3.5.2 The effects of the reading task on saccade lengths

Similar to the analysis of error rates and fixation durations, we ran a 2 (reading task: reading sentences versus strings of words) X 2 (spatial offset: left and right) X 2 (frequency: low and high) mixed-effects ANOVA on saccade lengths with reading task as a between-subject variable (on those trials in which the probe occurred with a temporal offset of 40 ms).

There was an effect of reading task ($F(1,24) = 35.01$, $p = 0.001$): the average saccade lengths was 7.03 characters (*SEM* = 0.31) and 4.42 (*SEM* = 0.26) for the tasks of reading sentences and reading strings of words, respectively. There was an interaction between spatial offset and task ($F(1,24) = 11.27$, $p = 0.003$). We broke down this interaction for different levels of task. There was no effect of spatial offset for the task of reading strings of words: the average length was 4.2 characters (*SEM* = 0.36) and 4.5 characters (*SEM* = 0.30) for left and right probes, respectively ($p = 0.129$). On the other hand, there was an effect of spatial offset for the task of reading sentences ($p = 0.005$): the average length was 7.3 characters (*SEM* = 0.33) and 6.7 characters (*SEM* = 0.30) for left and right probes, respectively. Therefore, right probes shortened saccades more than left probes but only when reading sentences.

5.4 Discussion

For the task of reading strings of random words, fixation durations on target words, Wn, were longer for low- than high-frequency words, confirming that reading occurred. Therefore, our probing paradigm was valid and did not disturb the processing of words at lexical levels for the task of reading strings of words. The results suggest that our version of the dynamic-orienting paradigm (Fischer, 1999) can be used to study attention in different reading tasks.

For the task of reading strings of words as opposed to sentences, the speed of reading (characters per seconds) was smaller, fixation durations were longer, saccades were shorter and landing positions were shifted more towards the beginning of the word confirming that the former was a harder task. Thus, we concluded that the perceptual span was narrower for the task of reading strings of words than reading sentences given that the span is narrower for harder tasks (Häikiö et al, 2009; Inhoff et al., 1989). In addition, an effect of the orthographic familiarity of the first trigrams in target words on the landing position on them confirmed that target words were previewed.

5.4.1. Attention

The amplitude of attention was not affected by the reading task for either left or right probes occurring 40 ms into a fixation. Thus, we concluded that attention was not focused on the gaze more for the task of reading strings of words than sentences early in a fixation (at temporal offsets of 40 ms). This does not contradict a narrower perceptual span for the former task. It is possible that (i) later during the engagement phase and/or (ii) during the orienting phase the perceptual span expands more rapidly on the right of the gaze location for the task of reading sentences than strings of words.

When reading string of words, similar to reading sentences, attention was skewed towards the right of the gaze location. Thus, attention was asymmetric around the gaze from the beginning of a fixation. In addition, the amplitude of attention, 6 characters from the gaze location, increased from 10 to 40 ms into a fixation; thus, we concluded that the focus of attention expanded over time. Furthermore, the amplitude of attention, 6 characters from the gaze location, was smaller when the fixated word was lower in frequency; thus, we concluded that attention was focused on the gaze location more when the fixated word was low rather than high in frequency, early in a fixation (at temporal offsets of 10 and 40 ms; Ghahghaei et al., 2013). Thus, the amount of preview that was obtained for the words was sufficient to reveal an effect of frequency on the focus of attention.

The effect of frequency on the focus of attention, 40 ms into the fixation, was stronger for the task of reading sentences than strings of words, as revealed by a two-way interaction between task and word frequency. Thus, the reading task modulated the effect of frequency on the focus of attention early in a fixation. Although we did not get an interaction between task, frequency and spatial offset, the observed two-way interaction was mostly because of a greater effect of frequency for left probes when reading sentences (Ghahghaei et al., 2013). For the task of reading strings of words, on the other hand, 40 ms into a fixation, the effect of frequency was not different for left and right probes.

There was a marginal effect of the orthographic familiarities of the first trigrams in target words on the focus of attention indexed by poorer performance on the probe when the first trigrams were orthographically less familiar; the statistical power of this effect was low. One explanation for this effect could be that in some trials the preview of target words was small and word processing was delayed so that the orthographic familiarity of the first trigram in the word affected attention only *after* the word was fixated. This effect could also be explained by some residual effects from the attentional distribution *before* the word was fixated. Shortly before a word was fixated, less attention remained at the gaze location if the first trigram in the word was more demanding when reading sentences (results from Experiment 3). It is possible that the orthographic familiarity of first trigrams in a word affected attention before the eyes landed on the word, for the task of reading strings of words as well, given that preview of target words when read strings of words was sufficient to affect where the eyes landed on target words: the eyes landed closer to the beginning of the words when the first trigrams in the words were orthographically less familiar. Therefore, it is possible that this effect of the orthography of the first trigram of the word on attention, before the word was fixated, carried on, after the word was fixated.

5.4.2. Eye-movement behaviours

Left probes prolonged fixations more than right probes, as we expected. In addition, fixation durations were longer for temporal offsets of 40 ms than 10 ms when the probe occurred on the left side of the gaze. We did not expect this given that there was no effect of temporal offset on fixation durations for peripheral probes occurring with a temporal offset of 10 ms (Experiment 2) or 40 ms (Experiments 1) in reading sentences. Thus the reading task (e.g., reading sentences versus random words) modulated the effects of the probe on saccade programming.

Saccade lengths were shorter for reading strings of words than sentences. Given that attention leads the eyes (e.g., Bryden, 1961; Deubel & Schneider, 1996; Fischer, 1999; Gersch, Kowler & Dosher, 2004; Hoffman & Subramaniam, 1995; Kowler & Blaser, 1995) this suggests that, at least during the orienting phase, the span was narrower on the right side of the gaze for the task of reading strings of words than sentences.

There was no effect of either the load of the fixated word or the temporal offset of the probe on saccade lengths. In addition, there was no effect of the spatial offset of the probe on saccade lengths. Given that saccades were shorter for the task of reading strings of words than sentences, a + 6 probe was less likely to have occurred between the gaze location and the intended saccadic target for the task of reading strings of words. It is known that when an abrupt-onset stimulus occurs away from the saccadic target, the saccadic metrics are affected by it less than when it occurs between the current gaze location and the next saccadic target (Walker et al., 1997). Therefore, right probes shortened the saccades less for the task of reading strings of words than sentences. Consequently, there was no effect of the spatial offset of the probe on saccade lengths for the task of reading strings of words.

5.5 Next Experiment

In Experiment 4, we showed that even when the reading task was to read strings of random words, a task which was harder than reading sentences, participants received sufficient preview to reveal an effect of frequency on the focus of attention, early in a fixation. Therefore, manipulating the task did not strongly affect the amount of the preview that was needed to reveal an effect of frequency on the focus of attention. In other words, manipulating preview by manipulating the load of the task was not a sufficiently strong manipulation to prevent the effect of frequency on attention. In Experiment 5, we directly manipulated the availability of preview by denying valid preview of the words, using a one-word moving-window paradigm.

Chapter 6

The effects of preview on the focus of attention

6.1 Introduction

Results from Experiment 4 showed that, early in a fixation, attention was focused on the gaze location more when the fixated word was low rather than high in frequency, for the task of reading strings of words. This is in line with the early effect of frequency on the focus of attention, in Experiments 1 and 2, for the task of reading sentences (Ghahghaei et al., 2013). We reasoned that this early effect of frequency arose presumably because processing of a word started before it was fixated. In other way of saying, participants previewed the word in the parafovea before fixating it (e.g., Rayner, 1982; Zola, 1980). Consequently, given preview, processing of the fixated words was sufficiently advanced to reveal an effect of the word's frequency on attention, early in a fixation, both for tasks of reading sentences and strings of words. Thus, manipulating preview by manipulating the reading task was not a sufficiently strong manipulation to prevent the effect of frequency on the focus of attention (the results from Experiment 4).

In Experiment 5, we directly manipulated the validity of preview using a one-word moving window paradigm. For the primary task, participants read strings of random words, as in Experiment 4, but now in a one-word moving window paradigm (we explain in section 6.2.3 why we chose a one-word moving window paradigm; McConkie & Rayner, 1975). So, words were exposed only when they were fixated (blank spaces were preserved; see Figure 6.1). Consequently, participants did not receive any valid preview of words.

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 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 survival percentage curves versus the duration of first fixations for when the fixated target word was either high or low in frequency. When the preview of the target word was valid, the survival curves for low- and high-frequency words diverged at about 145 ms. When preview was invalid, on the other hand, the survival curves diverged at about 256 ms. If saccade planning takes about 150 ms or so, Reingold et al.'s (2012) finding means that without a valid preview frequency information was not available when the word was fixated for the first time.

We expected that when valid preview was denied, the frequency of the word should no longer affect the focus of attention, early in a fixation (e.g., at temporal offsets of 10 ms and 40 ms). In the absence of valid preview, the processing of the word should start only after it was fixated. Thus, early in a fixation (i.e., at temporal offsets of 10 ms and 40 ms), the word processing would not be sufficiently advanced to reveal an effect of frequency on attention.

We probed attention, 6 characters from the gaze location, early in a fixation (at temporal offsets of 10 ms and 40 ms). The reading task was to read strings of random words for identification, in a one-word moving-window paradigm. The secondary task was unspeeded discrimination of the orientation of the probe. Given that we used the frequency/orthography/words stimulus set, the frequency of target words, and the orthographic familiarities of their first trigrams were orthogonally manipulated. Thus, Experiment 5 was a 2 (spatial offset: -6 and +6 characters) X 2 (temporal offset: 10 ms and 40 ms) X 2 (frequency of Wn: low and high) X 2 (orthographic familiarity of the first trigram in Wn: low and high) design.

We refer to the participants who performed Experiment 5 as the *invalid-preview group*. This is because preview of words was invalid for this group. In Experiment 4, preview of words was valid; thus, we refer to the participants who performed Experiment 4 as the *valid-preview* group. We looked at the effects of preview by comparing the results of the valid-preview (Experiment 4) and the invalid-preview (Experiment 5) groups.

We now sharpen our predictions in terms of attention. We expected that attention (i) would be asymmetric around the gaze and (ii) would expand over time (from 10 ms to 40 ms into a fixation). This is because the focus of attention was asymmetric around the gaze and attention defocused, over time, independent of the reading task (results of Experiments 1, 2 and 4).

We expected no effect of the orthographic familiarity of first trigrams in target words on the focus of attention. This is because, when preview was invalid, processing of the words started only after they were fixated. Thus, the orthographic familiarity of the first trigram in the word could not affect attention before the word was fixated; note that it could affect attention, before the word was fixated when preview was valid (results from Experiment 3). After the word was fixated, we expected that attention should be allocated to all letters in the word in parallel (e.g., LaBerge, 1983). Thus, we did not expect that the first trigram in the word would receive a higher priority for processing than other combinations of letters in the word. Consequently, we did not expect an effect of the orthographic familiarity of the first trigram on attention.

Most importantly, we expected that the frequency of the fixated word would no longer affect the focus of attention, early in a fixation (at temporal offsets of 10 ms and 40 ms). Given that there was an effect of frequency for the valid-preview group (results from Experiment 4), we expected to see an interaction between preview and word frequency.

It is possible that not obtaining any preview increases the processing load of a word, just after it is fixated. This being the case, we would expect that attention should be focused on the gaze more when preview is invalid than valid. On the other hand, it is possible that early in a fixation the processing load of a word is lower when preview is invalid than valid. This being the case, we would expect less focused attention around the gaze location for the invalid- than valid-preview group. We left this to be shown by the data.

We now sharpen our predictions in terms of eye-movements behaviour. Without valid preview, reading was expected to slow down. This is because processing of words is delayed when preview is invalid than valid. For the same reason, we expected that the duration of the first fixation on target words would be longer when preview was invalid than valid (the preview benefit; Rayner, 1975a, 1975b). Based on the results in Experiment 4, we expected that left probes would prolong fixations more than right probes. In addition, left probes occurring with a temporal offset of 40 ms were expected to prolong fixations more than left probes occurring with a temporal offset of 10 ms (inducing an interaction between spatial and temporal offsets).

Preview was not expected to affect saccade lengths given that (i) the decision on the length of a saccade is mostly affected by low spatial frequencies information (e.g., Reichle, Warren & McConnell, 2009) and (ii) low spatial frequency information (i.e., word boundaries) were the same for valid- and invalid-preview groups give that word boundaries were preserved. Thus, based on the results of Experiment 4 (the valid-preview group), we did not expect any effects of the spatial and/or temporal offsets of the probe or word frequency on saccade lengths.

Most importantly, we expected an effect of frequency on the duration of first fixations on target words, independent of the validity of preview. An effect of frequency would document that reading occurred (Rayner & Raney, 1996).

6.2 Method

6.2.1 Participants

Fifteen native mono-lingual English-speakers participated in Experiment 5 (all students in San Francisco; 9 female). They were all between 18 and 30 years old. They received money for their participation.

6.2.2 Apparatus

Same as in Experiments 3 and 4.

6.2.3 Stimuli

Similar to Experiment 4, participants read strings of words from the lists that were made based on the frequency/orthography/words stimulus set. The lists were made the same way we made the lists in Experiment 4. The preview of the words was always invalid.

In the literature of reading, the validity of preview is modulated using a moving-window paradigm (McConkie & Rayner, 1975) or a boundary paradigm (Rayner, 1975). When preview is valid, there is no change in the target words. When preview is invalid, in the boundary paradigm, the letters of target words are masked before the words are fixated and become unmasked upon the first saccades to the words. In the moving-window paradigm, all the letters outside a predefined window around the gaze location are masked.

In our study, if the change only occurred for the target word (here, Wn) in each string of words, and not for other words, participants might be cued by the change to expect the probe. This could change the task priorities. Therefore, we denied valid preview not only for the target word but also for all the words in the string.

If the words remained unmasked after the eyes left them, there would be an undesired asymmetry around the fixated word. In this case, the strings on the left side of the fixated word would make real words, whereas, the strings on the right side would not. To avoid this asymmetry, we masked the words again after the eyes left them. Consequently, the words were unmasked only when the eyes were within the word's boundaries. In other way of saying, we used a one-word moving window paradigm.

All letters in a word were masked by random consonants and were only unmasked when participants looked directly at them, Figure 6.1. Consonants occurred with the same frequency that consonant letters occur in English texts [21]. The word was masked again when the eye moved to another word. Word boundaries were preserved.

6.2.4 Design

Each string of words contained a target word. Target words were either low- or high-frequency. The orthographic familiarities of the first trigrams in the target words were either high or low. The probe occurred with a temporal offset of 10 ms or 40 ms from the beginning of the first fixation on Wn. Given that we were interested in the effects of the load of the fixated word on attention, Wn was the target word in Experiment 5. The probe occurred with a spatial offset of -6 or +6 characters from the gaze location. Thus, Experiment 5 was a 2 (frequency) X 2 (orthographic familiarity of the first trigram) X 2 (temporal offsets) X 2 (spatial offsets) design. For each level of the processing load of the target word (its frequency and the orthographic familiarity of its first trigram), there were 88 strings of words. Therefore, for each level of the experimental design, there were 22 samples. For each participant, a list of 352 strings of words was made with a randomized order of the experimental conditions. Each participant was presented with a different list.

Experiments 5 was run in three sessions, preferably in two separate days. If separate days were not possible, participants had a 1-hour break between the sessions.

[21] We used this website to calculate letter frequencies:
http://en.wikipedia.org/wiki/Letter_frequency#Relative_frequencies_of_letters_in_the_English_language

6.2.5 Procedure

The procedure was very similar to Experiment 4 (the valid-preview group). For the primary task, each participant read strings of words; see Figures 6.1. One string of words was presented on the screen at a time. Strings of words were left aligned. Participants were asked to read the words in silence. In 25% of the trials, participants answered an *identification* question *after* they read the string of words. Participants were asked whether or not a specific word was presented in the string of words they just read. The word to be identified was always chosen from the first or the last two words in the string of words and was never the target word. Participants were not informed about this. They were frequently reminded to read with their normal speed of reading; that is, not very slow and not very fast.

Gaze-contingent probes occurred when the eye landed on Wn, which was the target word in Experiment 5. The secondary task was to discriminate the orientation of the probe after they read the string of words. Participants were informed that the probe only occurred in the periphery and not at the gaze location.

In the beginning of the first session, participants received a long block of practice trials in which for the primary task they read two sets of *sentences* (ten and thirty sentences, respectively) for comprehension (as in Experiments 1-3). All target words in these sentences were high in frequency. The probe always occurred with a temporal offset of 40 ms and a spatial offset of -6 or +6 characters. Participants received verbal feedback on their performance on the probe.

Note that the luminance of the probe was adjusted based on the performance on the probe in reading sentence rather than strings of words. The reason we did this is that, we wanted the overall performance on the probe in Experiments 5, where participants read strings of words with an invalid preview, to be comparable with the overall performance on the probe in Experiments 4, where participants read strings of words with valid preview. Therefore, we used the same procedure to choose the luminance of the probe that we did in Experiment 4.

To avoid the ceiling or the floor effect, the probe luminance was adjusted for each participant during these practice trials to maintain about 75% accuracy on the probe. After the luminance of the probe was adjusted, each participant read a set of

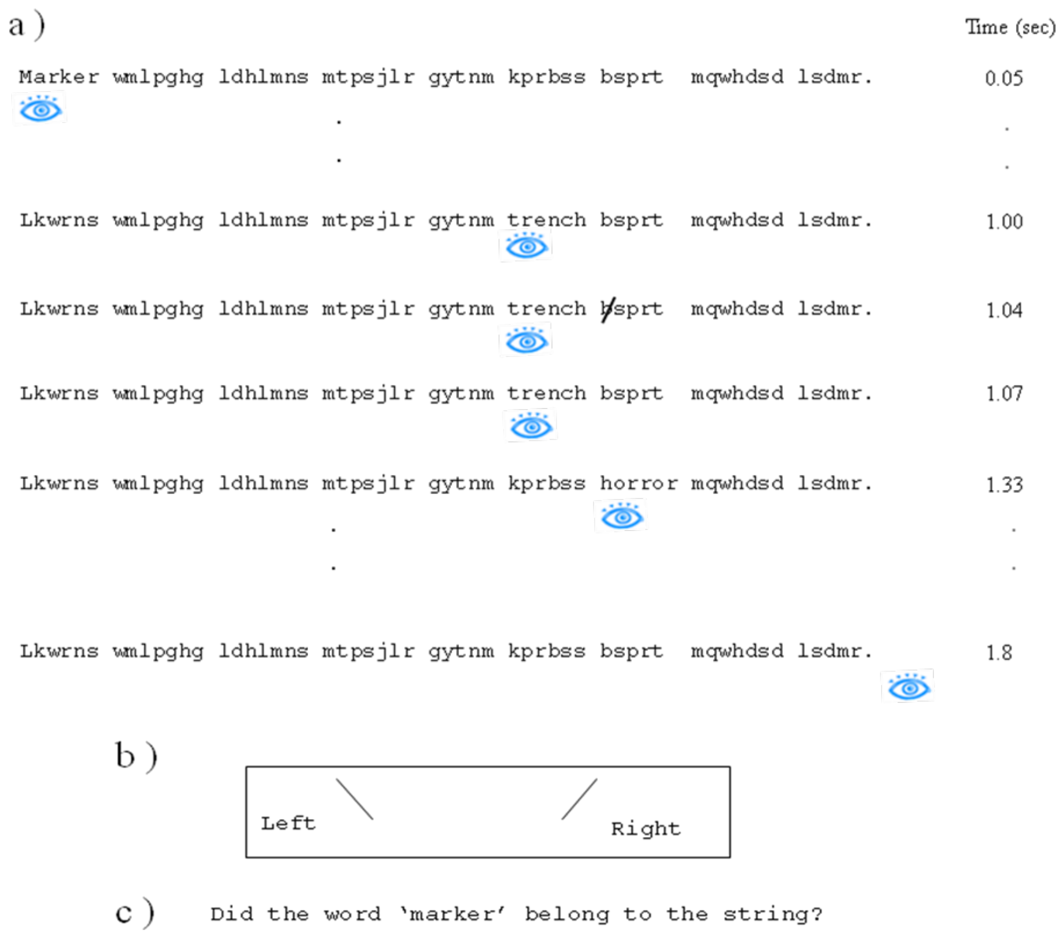

Figure 6.1. A schematic representation of one trial in Experiment 5. One string of words at a time was presented on the screen (a). Participant read the string in silence. The words were exposed only when they were fixated. There was a target word in each string, here the word 'trench'. Frequency of the target word was either high or low; here 'trench is a low-frequency word. The orthographic familiarity of the first trigram in the target word was either high or low; here 'tre' is high in orthographic familiarity. After some temporal offsets (here a temporal offset of 40 ms) from the beginning of the first fixation on the target word, the probe occurred 6 characters from the gaze, here on the right. The probe was only presented for 30 ms. Participants were instructed to (i) try not to be distracted by the probe and (ii) continue reading. After the string disappeared, another screen appeared and asked about the orientation of the probe (b). After the response to the probe was made, in 25 % of the trials, another screen appeared and participants were to verbally answer ('yes' or 'no') identify whether a specific word was presented in the string (c).

twenty *strings of words* with valid preview, for practice. Each string was followed by an identification question. Then, participants read another set of twenty strings of words, for practice, with an *invalid* preview. All participants found the reading task easy and learnt it quickly. In addition, in the beginning of each session, participants read a set of twenty strings of words with an invalid preview, for practice. We did not ask participants whether they were aware of the display change during the main blocks of the experiment. Given that a fluent reading highly depended on the efficiency of the calibration, the eyelink calibration routine was performed every twenty trials or whenever participants encountered a difficulty in reading.

6.3 Results

Participants who had more than 40% or less than 10% error on performance on the probe were excluded. Participants who had 2 or more sessions with less than 60 % accuracy on the probe were excluded in the analysis. As a result, 13 participants (the invalid-preview group; 8 female) in Experiment 5 were included. Trials were included if (i) the target word, Wn, was fixated, (ii) the first fixation on Wn was longer than 100 ms, and (iii) was followed by a forward saccade – the filtering criteria. From a total of 4389 trials, 3912 trials were included due to the filtering criterion (89 %). For a 2 (word frequency: low and high) X 2 (orthographic familiarity of the first trigram: low and high) X 2 (spatial offset: -6 and +6) X 2 (temporal offset: 10 ms and 40 ms) repeated-measures design, the average number of accepted trials per condition per participant was 18.8 (*SEM* = 0.4) samples.

We first looked at the effect of the validity of preview on the speed of reading by running a *t*-test on the speed of reading for the valid-preview group (i.e., participants in Experiment 4) and the invalid-preview group (i.e., participants in Experiment 5) with preview as the between-subject factor (section 6.3.1).

Then, for the invalid-preview group (Experiment 5), we ran a 2 (word frequency: low and high) X 2 (orthographic familiarity of the first trigram: low and high) X 2 (spatial offset: -6 and +6) X 2 (temporal offset: 10 ms and 40 ms) on error rates, fixation durations and saccade lengths. For each DV (error rates, fixation durations and saccade lengths), we also looked at the effects of preview by running a 2 (preview: valid and invalid) X 2 (word frequency: low and high) X 2 (orthographic familiarity of the first trigram: low and high) X 2 (spatial offset: -6 and +6) X 2 (temporal offset: 10 ms and 40 ms) mixed-effects ANOVA, with preview as a between-subject variable on that DV (section 6.3.2).

6.3.1 The speed of reading

A *t*-test was run on the speed of reading to examine the effect of preview. The speed of reading was bigger for the valid-preview (*mean* = 16.94 characters per second; *SEM* = 1.21) than the invalid-preview (*mean* = 15.35 characters per second; *SEM* = 0.44) group but the difference was not significant ($p = 0.22$). Nevertheless, the speed of reading was reduced by almost 10 % when valid preview was denied.

6.3.2 Error rates

First error rates in Experiment 5 are analysed (section 6.3.2.1). Then, effects of preview on error rates are analysed (section 6.3.2.2).

6.3.2.1 Error rates in Experiment 5

Error rates are shown in Figure 6.2. There was an effect of spatial offset ($F(1,12) = 15.45$, $p = 0.002$, $\eta^2 = 0.18$): the average error rate was 34.92 % (*SEM* = 2.45) and 24.39 % (*SEM* = 1.75) for the left and right probes, respectively. Therefore, attention was asymmetric around the gaze. There was an effect of temporal offset ($F(1,12) = 29.03$, $p = 0.001$, $\eta^2 = 0.15$): the average error rate was 34.50 % (*SEM* = 1.87) and 24.78 % (*SEM* = 1.91) for temporal offsets of 10 ms and 40 ms, respectively. Thus, attention defocused over time. There was no effect of frequency ($p = 0.743$) or orthographic familiarities of the first trigrams ($p = 0.241$). Therefore, as we expected, in the absence of valid preview, frequency did not affect the focus of attention. There was no other effects or interactions (all *p*-values > 0.05).

6.3.2.2 The effects of preview on error rates

The effects of spatial and temporal offsets of the probe were significant for both the valid-preview and the invalid-preview groups and, therefore, were significant in the combined data with preview as a between-subject variable.

There was no effect of preview ($p = 0.66$) on error rates: the average error rate was 29.2 % (*SEM* = 1.4) and 29.6 % (*SEM* = 1.4) for the valid- and invalid-preview groups, respectively. There was an effect of frequency ($F(1,24) = 10.88$, $p = 0.003$, $\eta^2 = 0.013$): the average error rate was 31.02 % (*SEM* = 1.16) and 27.90 % (*SEM* =

1.07) for low- and high-frequency words, respectively. The effect of frequency interacted with preview ($F(1,24) = 8.22$, $p = 0.008$, $\eta^2 = 0.010$): the effect of frequency was only significant for the valid-preview group, as we expected.

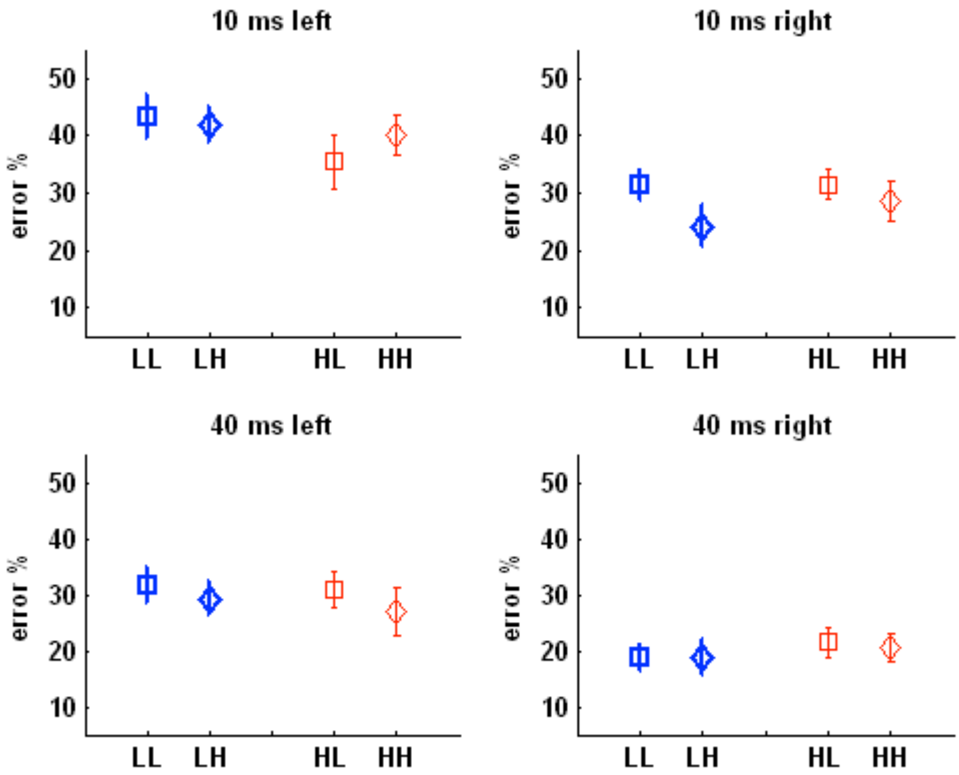

Figure 6.2. Error rates in Experiment 5.Performance on the probe, for the task of reading strings of words without valid preview, is shown for left (left panels) and right (right panels) probes with temporal offsets of 10 ms (top panels) or 40 ms (bottom panels). Performance is broke down across low (blue lines) and high (red line) frequency target words, for where the first trigram in target words was orthographically low familiar (squares) or high familiar (diamonds). Error bars show one standard error of the mean.
LL: low frequency target words beginning with orthographically low familiar trigrams
LH: low frequency target words beginning with orthographically high familiar trigrams
HL: high frequency target words beginning with orthographically low familiar trigrams
HH: high frequency target words beginning with orthographically high familiar trigrams

Furthermore, there was an interaction between preview and temporal offset ($F(1,24) = 8.58$, $p = 0.007$, $\eta^2 = 0.014$). To investigate this interaction, we looked at the effect of preview on the rate of the defocusing of attention, indexed by the difference in performance on probes occurring with a temporal offset of 10 ms with probes occurring with a temporal offset of 40 ms. We ran a one-way ANOVA with preview as a between-subject factor on the rate of defocusing. There was a significant effect of preview on the rate of defocusing ($F(1, 24)=52.18$, $p = 0.001$, $\eta^2 = 0.34$): the average difference between performances on probes occurring with temporal a offset of 10 ms and those occurring with a temporal offset of 40 ms was 10.91 % (*SEM* = 2.96) and 16.39 % (*SEM* = 4.96) for the invalid-preview and the valid-preview groups, respectively. Hence, defocusing was slower for the invalid-preview than the valid-preview group. There was no other effects or interactions ($p > 0.05$).

6.3.3 First fixation durations on target words (Wn)

First fixation durations in Experiment 5 are analysed (section 6.3.3.1). Then, effects of preview on fixation durations are analysed (section 6.3.3.2).

6.3.3.1 First fixation durations in Experiment 5

The average durations of the first fixation on target words are shown in Table 6.1. There was an effect of frequency ($F(1,12) = 8.53$, $p = 0.013$, $\eta^2 = 0.024$): the average fixation duration was 457 ms (*SEM* = 12) and 435 ms (*SEM* = 12) for low- and high-frequency words, respectively. Therefore, reading occurred.

There was an effect of spatial offset ($F(1,12) = 32.24$, $p = 0.001$, $\eta^2 = 0.45$): the average fixation duration was 492 ms (*SEM* = 15) for left and 395 ms (*SEM* = 10) for right probes. There was an effect of temporal offset ($F(1,12) = 22.67$, $p = 0.001$, $\eta^2 = 0.025$): the average fixation duration was 434 ms (*SEM* = 11) and 457 ms (*SEM* = 12) for temporal offsets of 10 ms and 40 ms, respectively. There was an interaction between spatial and temporal offset ($F(1,12) = 10.99$, $p = 0.006$, $\eta^2 = 0.041$). We broke down this interaction for left and right probes. There was an effect of temporal offset for left probes ($F(1,12) = 17.97$, $p = 0.001$, $\eta^2 = 0.24$): the average fixation duration for left probes was 468 ms (*SEM* = 14) and 521 ms (*SEM* = 20) for temporal offsets of 10 ms and 40 ms, respectively. There was no effect of temporal offset for right probes ($p = 0.4$). Thus, the effect of temporal offset was only revealed for left probes, similar to the results in Experiment 4.

6.3.3.2 The effect of preview on fixation durations

The effects of spatial and temporal offsets and word frequency and an interaction between spatial and temporal offsets were significant for both valid- and invalid-preview groups; these effects/interactions were also significant in the combined data with preview as a between-subject variable.

The average fixation duration was 446 ms (*SEM* = 17) for the invalid-preview group and 432 ms (*SEM* = 17) for the valid-preview group but the difference was not significant (p = 0.555). Nevertheless, the difference was in the expected direction. There was no other reliable effects or interactions (p > 0.05).

Average FFD on target words, Wn (ms)					
Spatial offset (characters)		**-6 (left)**		**+6 (right)**	
temporal offset (ms)		**10**	**40**	**10**	**40**
Wn frequency	Wn orthography				
Low	**Low (LL)**	469	527	401	399
		16	*19*	*11*	*17*
	High (LH)	478	544	424	417
		18	*25*	*14*	*16*
High	**Low (HL)**	455	503	388	376
		14	*18*	*12*	*13*
	High (HH)	471	507	388	386
		16	*25*	*15*	*10*

Table 6.1. FFD on target words in Experiment 5. Mean fixation durations (in ms) are shown for left and right probes with a temporal offset of 10 ms or 40 ms. Performance is broke down for LL, LH, HL and HH target words. Standard errors of the means (SEM) are shown in italics.

6.3.4 Saccade lengths

First saccade lengths in Experiment 5 are analysed (section 6.3.4.1). Then, effects of preview on saccade lengths are analysed (section 6.3.4.2).

6.3.4.1 Saccade lengths in Experiment 5

The average saccade lengths are shown in Table 6.2. The average saccade length from the first fixation on target words, Wn, was 5.25 characters (*SEM* = 0.24). As we expected, a four-way ANOVA showed no significant effect ($p > 0.05$).

6.3.4.2 The effect of preview

There were no reliable effects or interactions ($p > 0.05$).

Average saccade length (characters)					
Spatial offset (characters)		**-6 (left)**		**+6 (right)**	
temporal offset (ms)		**10**	**40**	**10**	**40**
Wn frequency	Wn orthography				
Low	**Low**	5.17	5.46	5.28	5.30
		0.34	*0.27*	*0.23*	*0.25*
	High	5.69	5.18	5.432	5.44
		0.26	*0.34*	*0.28*	*0.25*
High	**Low**	4.99	5.13	5.08	5.25
		0.32	*0.33*	*0.27*	*0.28*
	High	5.33	5.10	5.10	5.32
		0.27	*0.30*	*0.21*	*0.26*

Table 6.2. SL in Experiment 5. Mean saccade lengths (in characters) are shown for left and right probes with a temporal offset of 10 ms or 40 ms. Performance is broke down for LL, LH, HL and HH target words. Standard errors of the means (SEM) are shown in italics.

6.4 Discussion

In the absence of valid preview, the duration of first fixations on target were longer for low- than high-frequency words, confirming that reading occurred (Rayner & Raney, 1996). The effect of preview on the duration of first fixations was not significant but was in the expected direction: first fixations were longer when preview was invalid than valid. In line with this, the effect of preview on the speed of reading was in the expected direction: the speed of reading reduced by almost 10 % when valid preview was denied. Thus, reading occurred and manipulating preview affected reading time.

6.4.1. Attention

Attention was skewed in the direction of reading (i.e., towards the right), from the very beginning of a fixation, in the absence of valid preview. The amplitude of attention, 6 characters from the gaze location, increased from 10 ms to 40 ms into a fixation; thus, we concluded that attention defocused, over time, on both sides of the gaze. This is in line with the results in Experiments 1, 2 and 4, in which preview was valid.

When valid preview was denied, early in a fixation (at temporal offsets of 10 ms and 40 ms), processing of the word was not sufficiently advanced to reveal an effect of frequency on attention; thus, we concluded that the focus of attention around the gaze was not affected by the frequency of the fixated word. An interaction between preview and frequency showed that frequency affected the focus of attention, early in a fixation (at temporal offsets of 10 and 40 ms), only when preview was valid.

Furthermore, there was no effect of the orthographic familiarities of the first trigrams in target words on the focus of attention for the invalid-preview group. In the absence of valid preview, the first three letters in a word are not very different from the other letters in terms of processing priorities. This is because the processing of all letters are believed to occur in parallel after the word is fixated (LaBerge, 1983) and any serial processing of letters can lead to reading deficiency (e.g., Arguin & Bub, 2005). Thus, when preview was invalid, the processing load of a word was more likely to be affected by the orthographic familiarity of 'the whole word' than the orthographic familiarity of 'the first three letters'. The orthographic familiarity of the whole word is always high for high-frequency words, but can be high- or low- for low-frequency words (White, 2008). We did not find any effect of frequency on the focus of attention for the invalid-preview group. However, as mentioned above, a frequency manipulation does not accurately represent a 'whole-word orthography' manipulation. Therefore, it remains possible that there is an effect of 'the whole-word orthography' on the focus of attention which we were unable to observe.

The defocusing of attention was faster for the valid- than the invalid-preview group: performance on the probe improved from temporal offset of 10 ms to 40 ms but this improvement was larger for the valid- than the invalid-preview group. A comparison between Figures 5.2 and 6.2 suggests that (i) for temporal offsets of 10 ms, probe discrimination was worse for the valid- than the invalid-preview group (ii) for temporal offsets of 40 ms, on the other hand, probe discrimination was better for the valid- than the invalid-group. Consequently, although on average there was no effect of preview on probe discrimination, there was an interaction between preview and temporal offset. The results suggest that, early in a fixation, the defocusing of attention over time was slower when preview was invalid than valid.

6.4.2. Eye-movement behaviour

The effects of the spatial and temporal offsets of the probe on fixation durations were similar for the valid-preview and the invalid-preview groups: (i) left probes prolonged fixations more than right probes and (ii) left probes occurring 40 ms into fixations prolonged fixations more than left probes occurring 10 ms into fixations.

Similar to the results of the valid-preview group, there was no effect of the spatial and/or temporal offsets of the probe on saccade lengths. Furthermore, saccade lengths were not affected by the validity of preview. This is in line with the literature that only low spatial frequency information is used for saccade programming (e.g., Reichle et al., 2009).

In sum, the results for the task of reading strings of words confirmed that (i) reading occurred, as evidenced by longer fixation durations on words with lower frequencies, independent of the validity of preview, and (ii) when preview was valid, participants did benefit from it. The results of Experiments 4 and 5 together suggest that (i) the ongoing processing load of the fixated word affects the focus of attention around the gaze and (ii) this processing load and, therefore, attention is modulated by preview.

Chapter 7

General Discussion

We investigated the dynamics of attention during the course of a fixation and the effects of load on these dynamics in reading. Following Morrison (1984), and considering that the availability of visual information from the fixated word is crucial for fluent reading during the first 60 ms or so of a fixation (the disappearing-/masked-text paradigm; Rayner et al., 1981, 2003, 2006), we assumed that, early in a fixation, attention is engaged with the fixated word. Given that visual information from the fixated location is unlikely to be utilized for further processing by 120 ms into a fixation (as suggested by the switching-text paradigm; Blanchard et al., 1984), we proposed that, from halfway into the fixation, attention started to orient towards the to-be-fixated location and, presumably, to engage with the upcoming word. In sum, we assumed two phases for attention: the engagement phase, during which attention is engaged with the processing of the fixated word, and the orienting phase, during which attention orients away from the fixated location and engages with the processing of the upcoming word.

We probed attention, during both engagement and orienting phases, using a secondary task adopted from Fischer's (1999) study. Our probing technique was a valid and powerful technique given that (i) reading occurred despite probing and (ii) it revealed the dynamics of attention and the effects of load (i.e., frequency of target words and orthographic familiarity of their first trigrams).

In section 7.1, the validity and power of the technique we used is discussed. Section 7.2 is a review of our findings in terms of the dynamics of attention. Section 7.3

summarises the interference exerted by the probe on saccade programming. In section 7.4, we propose the Load-Dependent Dynamics (LDD) model of attention in reading. This is followed by a summary of our contribution to the fields of attention and reading, in section 7.5, and the future horizons of this work, in section 7.6.

7.1 The dynamic-orienting paradigm: a valid and powerful technique

We argue that reading was not disturbed by the probing and that the probe revealed the dynamics of attention in reading.

7.1.1 Reading occurred

Reading is indexed by an effect of frequency on fixation durations (e.g., Rayner, 1998; Reingold et al., 2010; Sereno, 1992; Staub et al., 2010); in other words, only if reading occurs, are fixation durations longer on low- than high-frequency words (Rayner & Raney, 1996). Thus, the demonstrated effect of frequency on first fixation durations on target words confirmed that reading occurred.

Regardless of the reading task (i.e., reading sentences or strings of random words), the validity of preview, or the spatial or temporal offsets of the probe, the duration of first fixations on target words were longer on low- than high-frequency target words. This effect of frequency was significant in (i) Experiments 1 and 2, where participants read sentences and the probe occurred after the eyes landed on target words; (ii) Experiment 2, control trials, where there was no probe; (iii) Experiment 3, where participants read sentences and the probe occurred during a single fixation on the words that preceded the target words; (iv) Experiment 4, where participants read strings of random words and the probe occurred after the eyes landed on target words; and (v) Experiment 5, where participants read strings of random words, with an invalid preview, and the probe occurred after the eyes landed on target words.

This frequency effect is in line with the findings in Fischer's (1999) study; using the dynamic-orienting paradigm, Fischer found an effect of frequency on the duration of single fixations during which the probe occurred. Given that the dynamic-orienting paradigm preserves the effect of frequency on fixation durations both in our data and Fischer's (1999) data, we believe that it is a valid paradigm to study attention in reading.

7.1.2 The dynamics of attention and the effects of load on these dynamics

In Fischer's (1999) study, the reaction time to detect the probe was the measure of attention. While this measure was sensitive to the profile of attention in a reading-like search task, it was not sensitive to this profile in reading. We adapted Fischer's paradigm and, for the secondary task, we used (unspeeded) discrimination accuracy on the probe as the measure of attention. Our version of the dynamic-orienting paradigm was sensitive to the asymmetric profile of attention in reading (Ghahghaei et al., 2012; Rayner, 1975). In addition, our results revealed the dynamics of attention and the effects of word load (the orthographic familiarity of the first trigram in the word and frequency of the word) on these dynamics, for both reading sentences and strings of words. In conclusion, our version of the dynamic-orienting paradigm is a powerful technique for studying the dynamics attention in reading and is sensitive to the effects of load.

7.1.3 Did frequency affect attention or iconic memory?

One might argue that the probe was encoded into a preattentive memory store (i.e., iconic memory) and then attention operated on this iconic representation (e.g., Lachter & Durgin, 1999). This being the case, it could be that the registration of probe information in iconic memory was not affected by frequency but rather the retrieval of this information. One might then conclude that our paradigm did not reveal effects of frequency on the dynamics of attention.

To counter this, first, it should be noted that visual information about the probe was processed at higher levels than preattentive memory stages, as indicated by accurate probe identification (as opposed to mere detection). Secondly, if attention operated over a preattentive iconic memory, any effects of processing load should have been equal for left and right probes. However, this was not observed: load (frequency) effects were asymmetrically distributed for the task of reading sentences both during the engagement phase where the effect of frequency was revealed for left probes and during the orienting phase where the effect of frequency was revealed for right probes (see results from Experiment 1).

In sum, reading occurred and the dynamics of attention and the effects of load on these dynamics were revealed. In section 7.2, our findings on the dynamics of attention are provided, for both engagement and orienting phases.

7.1.4 Did word frequency affect spatial attention or short term memory or both?

Short-term memory (STM) is suggested to be "a store in which decisions are made, problems are solved and information flow is directed" (Attkinson & Shiffrin, 1971). Thus, the decision on the identity of the probe, and responses based on this decision, rely on STM. Likewise, information regarding the word that is being processed (e.g., the fixated word or the next word) needs to be encoded in STM for reading comprehension. Thus, in our studies, the stimulus in both the primary task (i.e., the word being processed) and the secondary task (i.e., the probe) needs to be encoded into STM. The capacity of STM is limited in terms of the number of units that can be stored (e.g., Miller, 1956; Pashler, 1988). If more STM resource is allocated to encode a low- rather than high-frequency word then less resource is available for the probe. Thus, it is possible that the observed effect of word frequency on the accuracy of probe discrimination is, at least partly, due to effects of word frequency on STM. In other words, it is possible that word frequency affected (i) spatial attention or (ii) STM or (iii) both.

If word frequency affects STM via any route other than spatial attention, then the direction of the effect should be independent of the location of the probe. In other words, an increase in word frequency should always either improve or impair performance on the probe. In our study, performance on the probe was worse when the fixated word was low rather than high in frequency during both engagement (Experiments 1 and 4, left and right probes) and orienting (Experiment 1, right probes) phases. There was one exception: in Experiment 2 , error rates on left probes were 23.5 % (*SEM* = 2.45 %) and 27.6 % (*SEM* = 2.41) for low- and high-frequency words, respectively, (orienting phase, pooled over temporal offsets of 180 ms and 220 ms; see Figure 3.2). The difference was not significant (t (21) =-1.51, p = 0.145). Nevertheless, better performance on left probes when the fixated word was low rather than high in frequency is compatible with a delayed shift of spatial attention from the left of the gaze location to the next saccadic target when the fixated word was low rather than high in frequency.

If this difference was significant, we could argue that the observed effect of frequency, at least during the orienting phase, could not be due to an effect of word frequency on STM. However, given that the difference was not significant, we acknowledge that an effect of word frequency on STM not mediated by spatial attention could have resulted in the observed effect of word frequency on the performance on the probe. Nevertheless, we cannot rule out that word frequency affected spatial attention.

7.1.5 Key aspects of the methods that could have affected the outcome

7.1.5.1 The choice of characteristics of the orientation probe (size, luminance, duration)

The size/luminance of the probe was set so that probe discrimination accuracy was approximately 75% for probes occurring with a temporal offset of 40 ms from the first fixation on a high-frequency word. A larger probe with a higher luminance or a longer duration would have resulted in higher discrimination accuracy. In other words, it would have made the probe less demanding to process and therefore less sensitive to the distribution of attention and the load of the reading task. A different kind of probe would have revealed a different profile of attention. For example, in Fischer's (1999) study, the probe was a bright asterisk and latencies to detect the probe were the measure of attention; this measure was not however capable of revealing (i) the asymmetric profile of attention around the gaze location in reading or (ii) the effect of word frequency on attention.

7.1.5.2 The measures used to determine reading comprehension (and, hence, motivate the reading portion of the task)

The experimenter was present during experimental sessions and gave the participants verbal feedback on their performance on the comprehension/identification questions and also frequently reminded them of how many wrong answers they had made. Participants could read each line of text only once and this, presumably, increased the priority of the reading task. There were 120 comprehension questions in Experiments 1 and 2; there were 100 comprehension/identification questions in Experiments 3, 4 and 5; almost all participants made less than 10 wrong answers.

If there had been less emphasis on the reading task (e.g., if participants had only been required to search through the text for a target word) we would have expected a different profile of attention. For example, given that word frequency does not affect fixation durations when participants just search through a text for a target word (Rayner & Raney, 1996), we would not expect an effect of word frequency on attention when participants search through the text. It is also possible that the effect of frequency would be reversed if the task was searching instead of reading for comprehension/identification. In other words, it is possible that participants would prioritize probe discrimination; if this were the case, we should expect to see better performance on the probe when the fixated word was more demanding. This would affect the corresponding AOC curve and show a trade-off between the primary task (i.e., reading) and the secondary task.

7.1.5.3 The predictability of the reading probe in both space and time

Except for Experiment 2, in all other experiments, there was a probe in each trial. In all experiments, the participants were led to believe that there was no probe in some trials. This presumably reduced their expectation of seeing a probe. They were instructed to press any button (left or right) at random if they did not see the probe.

In Experiments 1 and 2, the probe could occur at any given time (early or late) during a fixation; in Experiment 3, the probe could occur only late in a fixation; in Experiments 4 and 5, the probe could occur only early in a fixation. Thus, participants were more uncertain about when during a fixation the probe occurred in Experiments 1 and 2 (compared to in Experiments 3, 4 and 5). This uncertainty affected participants' decisions to move their eyes from the fixated word; it is possible that in each fixation participants delayed the upcoming saccade and waited for the probe to occur. If this were the case, we should have seen an increase in the duration of first fixations on words with increase in the temporal offset of the probe. This was not the case. Fixation durations decreased with temporal offset from 110 ms into a fixation onwards (Experiments 1 and 2).

The target word was presented around the midline of each line of text. It is possible that probe expectation increased as the participant read through each line of text. It is possible that the reading task was more prioritized early on and then later, as the eyes moved through the line of text, discrimination of the probe received more priority. In other words, it is possible that early during a trial, the participant read for comprehension but later in the trial, if the probe had not occurred, the participant scanned through the text, instead of reading for comprehension, as a result of allocating a higher priority to discriminating the probe. If this were the case, then as the target word moved rightwards in the line of text (i) fixation durations would have increased, and/or the effect of frequency on fixation duration would have changed or even disappeared (as an indicator of an interruption in processing words at lexical levels) and (ii) performance on the probe would have improved.

We investigated this in Experiment 1. The beginning of the target word was on average 38 characters from the beginning of the sentence (standard deviation of 11 characters, minimum of 14 characters and maximum of 60 characters) in the stimulus set used in this experiment. We divided trials into three groups depending on where the beginning of the target word was located in the sentence: the ‘ beginning’ group (occurring at less than 27 characters), the ‘middle’ group (occurring between 27 and 49 characters) and the ‘end’ group (occurring at more than 49 characters). To increase the statistical power of the analysis, and given that the spatial and temporal offset of the probe was randomized, we pooled over the levels of spatial and temporal offset. In Experiment 1, central probes occurred with temporal offsets of 110, 130 and 180 ms; peripheral probes occurred with temporal offsets of 40, 90, 110, 130, and 180 ms.

To address whether the performance on the probe was affected by the location of the target word, we looked at the effect of target word location on the accuracy of probe discrimination. We ran a 3-way (target word location: beginning, middle and end) repeated-measures ANOVA on error rates to discriminate the probe. There was no effect of the location of the target word (F (12, 42) = 0.50, $p >$ 0.5): the average error rate was 17.7 % (*SEM* = 1.4 %), 18.7 % (*SEM* = 1.5%) and 17.4 % (*SEM*= 1.5 %) for target words that were located at the beginning, middle and end of the line of text, respectively. Thus, the location of the target word did not affect the performance on the probe.

To address whether the reading task was affected by the location of the target word, we ran a 3 (target word location: beginning, middle and end) X 2 (word frequency: high and low) repeated-measures ANOVA on the duration of first fixations on target words. There was no effect of word location (F(2,42) = 1.45, p = 0.24): the average fixation on target words was 337 ms (*SEM* = 14) , 334 ms (*SEM* = 14) and 325 ms (*SEM* = 15) for words located at the beginning, middle and end, respectively. There was an effect of frequency (p = 0.001) which did not interact with the location of the word (p = 0.29). Thus, the reading task (i) was not slowed down or (ii) did not change from reading for comprehension to scanning through the text as the target word location moved further into the line of text.

Thus, we did not find any evidence to suggest an effect of an increasing expectation of the probe occurring on reading or on probe discrimination accuracy.

However, we acknowledge that it is possible that this expectation affected participants' reading strategies and affected other variables that we do not analyse here (e.g., the total reading time).

7.1.5.4 Dealing with blinks

Reading each line of text took around 2 to 4 seconds depending on the reading task (reading sentences or strings of words). Participants were given the possibility to use eye drops to prevent blinks resulting from dry eyes. They were asked to blink before starting a trial to prevent blinks during the trial. However, there were occasional blinks. Our analysis program did not identify whether or not there was a blink in a trial. A better analysis would have been one that excluded trials with blink(s) or determined whether blinks were confounded with the experimental manipulations.

7.2 The dynamics of attention in reading

Following Morrison (1984), we assumed two phases for attention: engagement and orienting. We proposed that, during the engagement phase, attention should be more focused on the gaze when the fixated word is low rather than high in frequency. By halfway through the fixation, we expected that attention would start orienting (during the orienting phase). We expected that attention would orient towards the next saccadic target earlier when the fixated word was high rather than low in frequency. Shortly before the saccade to the upcoming word, we proposed that attention would be engaged with the processing of the upcoming word and would be affected by the load of the upcoming: we expected that less attention would remain at the gaze location when the processing of the upcoming word was more demanding. Our findings for both engagement and orienting phases are reviewed in sections 7.2.1 and 7.2.2, respectively.

7.2.1. Attentional-engagement phase

We measured the amplitude of attention 6 characters to the left or right of fixation. The probe occurred with a temporal offset that ranged from 10 ms to 110 ms from the beginning of the first fixation on target words (Experiments 1, 2, 4 and 5). We manipulated the load of the fixated word (frequency, in Experiments 1, 2, 4 and 5; orthographic familiarity of first trigrams, in Experiments 4 and 5) to address the effects of load on attention.

In the perceptual-load literature (e.g., Brand-D'Abrescia & Lavie, 2007; Lavie, 1994, 1995; Madrid et al., 2011), the amplitude of attention is usually measured at a fixed distance from the gaze location. The effect of load on this amplitude is then interpreted as an effect of load on the *focus* of attention around the attended location. The idea is that, when attention is more focused, the amplitude of attention is smaller at a given peripheral location. Following this logic, we interpreted changes in the amplitude of attention 6 characters from the gaze location during the engagement phase (but not during the orienting phase) as changes in the focus of attention.

For the first time, we showed that attention was asymmetric around the gaze location from the very beginning of a fixation (i.e., at temporal offsets of 10 ms; Experiments 2, 4 and 5): there was more attention on the right (i.e., in the direction of reading in English texts) than on the left of the gaze location (Ghahghaei et al., 2013).

In addition, we showed that, during the engagement phase, the amplitude of attention increased over time on both sides of the gaze; thus, we concluded that attention defocused on both the left and the right sides of the gaze location (Ghahghaei et al., 2013). The defocusing of attention occurred (i) both for tasks of reading sentences (Experiments 1 and 2) and strings of words (Experiment 4) and (ii) when the preview of words was valid (Experiment 4) or invalid (Experiment 5) for the task of reading strings of words. Attention defocused from the earliest times that we measured attention (i.e., from temporal offsets of 10 ms to 40 ms).

This defocusing of attention further supported our assumption of two phases of attention in reading: during the engagement phase, attention expanded around the currently fixated location (i.e., it defocused); in contrast during the orienting phase, attention moved towards the to-be-fixated location (i.e., it oriented). Consequently, 6 characters to the left of the gaze location, the amplitude of attention increased over time during the engagement phase but decreased over time during the orienting phase. On the other hand, 6 characters to the right of the gaze location, the amplitude of attention increased over time both during engagement and orienting phases.

Attention defocused whether or not preview was valid, for the task of reading strings of words. Nevertheless, the defocusing of attention, from 10 ms to 40 ms into the fixation, was slowed down when valid preview was denied. Preview affects the timecourse of word processing and, consequently, the dynamics of attention. Early in a fixation, the change in processing load, over time, would be smaller when processing has just began (i.e., in the invalid-preview condition) than when it has been going on for a while (i.e., in the valid-preview condition). This should then result a slower defocusing of attention without valid preview.

Only when preview was valid, early in a fixation, did word frequency affect the load, and consequently attention, for the task of reading strings of words: the amplitude of attention, 6 characters from the gaze location, was smaller when the fixated word was lower in frequency. For the task of reading sentences, preview was valid and, again, the amplitude of attention 6 characters from the gaze location was smaller for low- than high-frequency words. We conclude that, early in a fixation (i.e., at temporal offsets of 10 ms and 40 ms) attention is more focused on the gaze location when the fixated word is low rather than high in frequency (Ghahghaei et al., 2013), when preview was valid.

This early effect of the frequency of a word on attention is contingent on (i) the word being previewed before being fixated (e.g., Inhoff et al., 2000; Rayner & Clifton, 2009; White et al., 2005; Results on probe performance in Experiment 3 and landing positions in Experiment 1 and 2) and (ii) word processing being integrated over the saccade to the word (e.g., Inhoff, Starr & Shindler, 2000; Rayner & Clifton, 2009). Consequently, there was no effect of frequency on the focus of attention early in a fixation (i.e., at temporal offsets of 10 ms and 40 ms; see results of Experiment 5) when valid preview of the words was denied. For the first time, we show that preview modulates the focus of attention and the effects of word frequency on this focus.

The effect of frequency on the focus of attention was modulated not just by preview but also by the nature of the reading task. For the task of reading strings of words, with valid preview (Experiment 4), the effect of frequency on attention was revealed, 40 ms into a fixation, both on the left and the right sides of the gaze location. However, for the task of reading sentences, 40 ms into a fixation, the effect of frequency was revealed only on the left side of the gaze (Experiment 1). Nevertheless, 10 ms into a fixation, when attention was more focused on the gaze, the effect of frequency was in the expected direction for both left and right probes, suggesting that on both sides of the gaze location the amplitude of attention was bigger for low-frequency than high-frequency words.

For the task of reading sentences, as attention defocused on both the left and the right sides of the gaze, the effect of frequency on performance on left probes increased from 10 ms to 40 ms into a fixation and ceased by halfway through the fixation (i.e., the temporal offset of 110 ms in Experiment 1). From halfway into a fixation onwards, attention oriented towards the to-be-fixated location and, presumably, engaged with the processing of the upcoming word.

7.2.2 Attentional-orienting phase

We probed the orienting phase of attention only for the task of reading sentences. We measured the amplitude of attention 6 characters to the left and right of the gaze location or at the gaze location. The probe occurred with varying temporal offsets from the beginning of the first fixation on either target words (110 ms to 220 ms; Experiments 1 and 2) or words that preceded target words (180 ms to 250 ms; Experiment 3). We addressed the effects of the load of the fixated word (frequency; Experiments 1 and 2) or the load of the upcoming word (frequency and orthographic familiarity of first trigrams and frequency; Experiment 3) on attention.

We expected that, during the orienting phase, attention should increase at the location of the next saccadic target and decrease elsewhere, over time. Late in a fixation, saccadic suppression affects (or degrades) perception (Erdmann & Dodge, 1898; Haber & Hershenson, 1973). Thus, late in a fixation, both orienting of attention and saccadic suppression should degrade perception at the gaze location or 6 characters to the left of the gaze. On the other hand, saccadic suppression and orienting of attention should function in opposite directions and partly cancel each other out, 6 characters to the right of the gaze location, which is close to the next saccadic target. Indeed, from 180 ms to 220 ms into a fixation, accuracy on probe discrimination decreased for left and central probes but not for right probes, suggesting an orienting of attention from the already-fixated locations and towards the to-be-fixated location (Experiment 2). To the best of our knowledge, this is the first report that directly addresses the timecourse of the orienting of attention in reading.

We expected that orienting of attention would be affected by the load of the fixated word. Given that (i) the eyes fixate longer on low-frequency words (e.g., Rayner, 1998; Reingold et al., 2010; Sereno, 1992; Staub et al., 2010) and (ii) attention leads the eyes (e.g., Doré-Mazars et al., 2004; Fischer, 1999; Hoffman & Subramaniam, 1995; Kowler et al., 1995), we expected that attention would orient towards the right earlier for high- than low-frequency words. In line with this, the results from Experiment 1 showed that 6 characters to the right of the gaze location, attention was greater when the fixated word was high rather than low in frequency, during the orienting phase (i.e., at temporal offsets of 110 ms, 130 ms and 180 ms; Ghahghaei et al., 2013). This is, to the best of our knowledge, the first report that shows the timecourse of an effect of word frequency on the orienting of attention in reading.

The effect of frequency, however, did not change over time. The results of Experiment 1 revealed (i) an effect of frequency but (ii) no interaction between frequency and temporal offset when right probes occurred with temporal offsets of 110 ms, 130 ms or 180 ms. It is possible that the statistical power of the analysis was insufficient to reveal any interaction. Furthermore, while right probes revealed an effect of the frequency of the fixated word during the orienting phase in Experiment 1, left or central probes did not. It is possible that frequency affects attention, at the gaze location and/or 6 characters to the left of the gaze, only after 180 ms into a fixation. However, 220 ms into the fixation, an effect of frequency was revealed neither for left and central probes nor for right probes (Experiment 2). It is possible that, 220 ms in a fixation, any effect of frequency on the orienting of attention was overwritten by saccadic suppression given that there was no effect of frequency even for right probes.

It is also possible that by 220 ms into a fixation, the load of the fixated word no longer affects the orienting of attention. Note that, late in a fixation, (i) the processing of the upcoming word has started (e.g., Inhoff et al., 2000; Rayner & Clifton, 2009; White et al., 2005) and (ii) this processing affects the programming of the saccade to the upcoming word (e.g., Radach et al., 2004; Vonk et al., 2000; White et al., 2006; Plummer & Rayner, 2012). Given that attention leads the eyes (e.g., Hoffman & Subramaniam, 1995; Kowler et al., 1995), we proposed that, shortly before the saccade to the upcoming word, attention should be affected by the load of the upcoming word. The results of Experiment 3 showed that, late in a single fixation on a word (i.e., during the last 100 ms), the processing load of the first trigram in the upcoming word affected attention at the gaze location: the more unfamiliar the first trigram was orthographically, the less attention remained at the gaze location. This is, to the best of our knowledge, the first report of an effect of the processing load of the to-be-fixated target on attention at the gaze location.

Our probing technique revealed the dynamics of attention and the effects of load on these dynamics both during the engagement and orienting phases. The probe, as an abrupt-onset stimulus, was expected to affect the programming of the upcoming saccade. In section 7.3, we review how fixation durations and saccades were affected by the probe.

7.3 Effects of the probe on the eyes

Accuracy on probe discrimination was the measure of attention in our study. The probe, as an abrupt-onset stimulus, was expected to affect the eyes (e.g., Findlay & Walker, 1999; Fischer; 1999; Walker et al., 1997). A review of the results on fixation durations and saccade lengths is provided in sections 7.3.1 and 7.3.2 respectively.

7.3.1 Fixation durations

Reingold and Stampe (2000, 2004) showed that fixation durations were prolonged some 70 ms after any display change in reading. Fischer (1999) also showed that fixations were prolonged in the presence of the probe. In our work, a comparison between control trials (i.e., those trials where the probe did not occur) and experimental trials (i.e., those trials where the probe did occur) in Experiment 2 showed that fixation durations were prolonged by the probe. Nevertheless, the effect of word frequency on the duration of the first fixations on target words was preserved, confirming that reading occurred (Rayner & Raney, 1996).

During the engagement phase, right probes prolonged the fixations less than left probes (Fischer, 1999; Ghahghaei et al., 2013; Walker et al., 1997) for the task of reading strings of words and sentences, regardless of word frequency. During the orienting phase, for the task of reading sentences (in Experiments 1 and 2; temporal offsets of 110 ms to 220 ms), there was no difference between probes occurring at the gaze location and those occurring 6 characters to the left of the gaze in terms of fixation durations. On the other hand, there was a difference between 'left and central' probes and right probes, which was significant in Experiment 1 for temporal offsets of 110 ms to 180 ms, regardless of the frequency of the fixated word ('left and central' prolonged the fixations more than right probes). In Experiment 2, for temporal offsets of 180 ms and 220 ms, this difference between 'left and central' probes and right probes was significant but only when the fixated word was low in frequency. This suggests that, when the fixated word was high in frequency, probes occurring with a temporal offset of 180 ms or 220 ms occurred close to the non-labile stage of saccade programming (Becker & Jürgens, 1979); so that the spatial offset of the probe no longer affected the timing of the upcoming saccade. In sum, the temporal offset of the probe modulated the effects of the probe on saccade programming. In general, probes occurring halfway into a fixation affected fixation durations more than those occurring earlier or later, presumably because they occurred during the labile stage of saccade programming.

In general, the effect of the temporal offset of the probe on fixation durations was clearer for left than right probes. For left probes, fixation durations (i) increased with temporal offset from temporal offsets of 40 ms to 110 ms, and (ii) decreased with temporal offset from temporal offsets of 110 ms to 180 ms, and (iii) did not significantly change with temporal offset between temporal offsets of 180 ms and 220 ms. For right probes, on the other hand, the effect of the probe on fixation durations was not significantly modulated by its temporal offset.

An attentional-based explanation for this could be that attentional resources were sufficiently available for the perception of right probes throughout a fixation; whereas, these resources were only sufficiently available for the perception of left probes around halfway through a fixation. This might be because by halfway through a fixation (i.e., at temporal offsets of 110 ms), attention defocused on both sides of the gaze; after that, attention oriented towards the right and away from the left and the gaze location. Thus, left probes received more attention around halfway through a fixation and, therefore, affected the timing of the upcoming saccade mostly around halfway through a fixation.

Given that attention defocused from very early in a fixation (Ghahghaei et al., 2013; Experiments 1, 2, 4 and 5), this interpretation suggests that left probes occurring 40 ms into a fixation should prolong fixations more than those occurring 10 ms into a fixation. This was the case for the task of reading strings of words, with or without valid preview, but not for the task of reading sentences. It is possible that, for the task of reading sentences, the statistical power of the analysis was insufficient to reveal an interaction between spatial and temporal offset, given that temporal offset was a between-subject variable (see section 3.3.2.5, temporal offset of 10 ms in Experiment 2 and 40 ms in Experiment 1). Another possibility is that the amplitude of attention increases on the left of the gaze location, from 10 ms to 40 ms into a fixation, less for the task of reading sentences than strings of words. In other words, one could assume that, early in a fixation, the perceptual span is less extended to the left of the gaze location when reading sentences than words. This was not revealed by comparing probe discrimination for the temporal offset of 40 ms in the tasks of reading sentences (Experiment 1) and strings of words (Experiment 4): there was no two-way interaction between task and spatial offset (section 5.3.2.2). Nevertheless, a narrower perceptual span on the left of the gaze location, for the task of reading sentences than strings of words, is in line with the effect of frequency on probe discrimination (i) being bigger for left than right probes, for the task of reading sentences (Experiment 1; Ghahghaei et al., 2012), but (ii) equal for left and right probes, for the task of reading strings of words (Experiment 4).

7.3.2 Saccade lengths

A comparison between control trials (i.e., those trials where the probe did not occur) and experimental trials (i.e., those trials where the probe occurred) in Experiment 2 showed that saccade lengths were shortened by the probe (also see Fischer, 1999). In the absence of the probe (Experiment 2, control trials), there was an effect of frequency on saccade lengths, for the task of reading sentences: saccades were shorter for low- than high-frequency words. This is compatible with more refixations on low- than high-frequency words (Pollatsek & Rayner, 1990) resulting in a smaller average saccade length.

The probe, as an abrupt-onset stimulus, competed with the intended saccadic target (e.g., Findlay & Walker, 1999; Fischer; 1999). Therefore, the effect of word frequency on saccade lengths was overwritten by the probe for some of the experimental conditions. It should be noted that an effect of frequency on saccade lengths (i) is compatible with reading (e.g., more refixations on low- than high-frequency words) but (ii) is not a hallmark of reading. In other words, not having an effect of frequency on saccade lengths does not mean that reading did not occur. Nevertheless, the effect of frequency on saccade lengths was preserved for (i) left or central probes occurring with a temporal offset of 180 ms or longer (Experiment 2), and (ii) right probes occurring with a temporal offsets of 110 ms or longer (Experiments 1 and 2), for the task of reading sentences.

For the task of reading sentences, right probes shortened saccades more than left or central probes, regardless of the temporal offset of the probe. For the task of reading strings of words, on the other hand, left and right probes, occurring with a temporal offset of 10 or 40 ms, shortened the length of the upcoming saccade equally, regardless of the validity of preview. One reason for not having an effect of spatial offset on saccade lengths in reading strings of words could be that fixation durations were relatively longer for both left and right probes when reading strings rather than sentences. It has been shown that when saccadic latencies increase, the next saccadic target is selected more accurately (Ottes, Van Gisbergen & Eggermont, 1984). Hence, one could say that long fixation durations helped the oculomotor system to make a more accurate decision about the next saccadic target, for the task of reading strings of words than sentences, for both left and right probes. This in turn eliminated the effect of spatial or temporal offsets on saccade lengths for the task of reading strings of words[22].

In the following, section 7.4, we suggest a load-dependent dynamics (LDD) model of attention, based on our results for the dynamics of attention during the course of a fixation.

7.4 Modelling attention in reading

There are many models of how eye movements are programmed/controlled in reading and how these movements are affected by different aspects of the text or the task. Some of these models assume that only the low-level visual attributes of the words (e.g., their lengths) affect eye movements; this group of models are called the oculomotor-based models of eye movement control (e.g., McConkie, Kerr & Dyre, 1994; Reilly & O'Regan, 1998). Some models also allow for a role of the lexical load of the words (e.g., word frequency) in programming the eyes; these groups of models are called the cognitive models of eye movement control in reading (Rayner, Sereno & Raney, 1996). Within the cognitive models, some assume that only one word can be processed at a time at lexical levels (e.g., the E-Z Reader model; Reichle, Pollatsek, Fisher, & Rayner, 1998; Rayner, Sereno, & Raney, 1996; Reichle, Rayner, & Pollatsek, 2003). Some, to the contrary, assume that more than one word at a time can be processed at lexical levels (e.g., the SWIFT model; Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005; Laubrock, Kliegl & Engbert, 2006; Nuthman & Engbert, 2009; Richter, Engbert & Kliegl, 2005). Although these models can explain and predict a range of eye-movement behaviour in reading and allocation of attentional resources at lexical levels, they are not designed to address spatial attention.

[22] The average fixation durations on target words were always longer for the task of reading strings of words than sentences. The longest average fixation duration for the task of reading sentences was 370 ms (i.e., the average fixation duration on a low-frequency word for left probes with a temporal offset of 110 ms; Table 2.1). The shortest average fixation duration for the task of reading strings of words with valid preview was 377 ms (i.e., the average fixation duration on a high-frequency word for right probes with a temporal offset of 10 ms; Table 5.1). Thus, even the biggest average fixation duration for the task of reading sentences was still smaller than the smallest average fixation duration for the task of reading strings of words.

In section 7.4.1, we briefly review the assumptions of the E-Z Reader and SWIFT model in terms of spatial attention. Then, in section 7.4.2, we provide our load-dependent dynamics (LDD) model of attention in reading.

7.4.1 E-Z Reader and SWIFT models

The E-Z Reader model assumes that pre-lexical processing of letters or their attributes can occur in parallel within an asymmetric perceptual span that is skewed in the direction of reading but is invariant over time. We interpret the perceptual span as being synonymous with spatial attention (Ghahghaei et al., 2013). According to this interpretation, the model's position is that spatial attention does not vary over time.

The SWIFT model assumes one span for pre-lexical processing and another span for lexical processing (see Schad & Engbert, 2012, for the latest version of the model). The model assumes that both spans are skewed in the direction of reading. On the left side of the gaze location, the model assumes that neither span varies in its extent over time. On the right side of the gaze location, the model assumes that (i) the extent of the lexical span varies over the course of a fixation and is affected by the load of the fixated word, whereas (ii) the extent of the pre-lexical span is fixed and independent of the load of the fixated word. We interpret the pre-lexical span in the SWIFT model as being synonymous with spatial attention. Therefore, we interpret the model's position as being that spatial attention does not vary over time and does not depend on the load of the fixated word.

7.4.2 The Load-Dependent Dynamics (LDD) model of attention

For the engagement phase, we had data for peripheral probes occurring with temporal offsets of 10 ms or 40 ms into a fixation for the task of reading (i) sentences, (ii) strings of words and (iii) strings of words with an invalid preview, when the frequency of the fixated word was manipulated. Given that, early in a fixation, we did not find an effect of orthographic familiarity of first trigrams in target words on the amplitude of attention for any of our experimental designs, we only modelled the effects of the frequency of the fixated word, but not the orthographic familiarity of its first trigram, on the amplitude of attention in the parafoveal region. Furthermore, we did not model the amplitude of attention at the gaze location given that we did not probe attention at the gaze location early in a fixation.

Assume that, for a given reading task, the processing load of a word from the time the processing starts, which is not necessarily the time it is fixated, is defined as

$$LoP(t,\tau) = te^{-t^2/\tau} \qquad \text{(Equation 1)}$$

where, $LoP(t,\tau)$ is the load of processing of the fixated word, t is the time from the beginning of the processing of the word and, and τ determines the speed of the processing. τ is a monotonically increasing function of word frequency. Given that we treated frequency as a categorical rather than a continuous variable in our study, we considered two τ values for low- and high-frequency words. The value of τ was bigger for low- than high-frequency words. The higher the τ, (i) the higher the load of the processing of the word would be, at a given time, and (ii) the longer the processing of the word would take; thus the longer the eyes would remain on the word.

$$\tau = \begin{cases} \tau_H \text{, for high-frequency words} \\ \tau_L \text{, for low-frequency words} \end{cases} \qquad \tau_H < \tau_L$$

The results of Experiments 1, 2, 4 and 5 showed that for the task of reading strings of words, with valid preview, first fixation durations (i) were considerably longer compared to the task of reading sentences, but (ii) were only slightly shorter compared to the task of reading strings of words with an invalid preview. Thus, the pair of (τ_H, τ_L) that we chose for the task of reading strings of words, with valid preview, were considerably bigger than the pair of (τ_H, τ_L) that we chose for the task of reading sentences, but were only slightly smaller than the pair of (τ_H, τ_L) for the task of reading strings of words, with an invalid preview. Table 1.7 shows the values of the parameters for the different types of reading task. Substituting these parameters in Equation 1, we calculated the processing load of a word, for the task of reading sentences, strings of words with valid preview, or strings of words with an invalid preview (Figures 7.1, 7.2 and 7.3., top panels).

Reading task :	**Sentences**	**Strings of words**	**Strings of words with an invalid preview**
τ_H	5000	7500	8000
τ_L	7000	12000	12800
p	50	40	0
σ_{left}	4	4	4
σ_{right}	15	10	9
α	0.175	0.14	0.14

Table 7.1. Parameters in the LDD model of attention. Parameters are provided for different levels of reading task. τ_H and τ_L control the processing load of the word for high- and low-frequency words, respectively. p denotes the preview benefit that a word obtains before it is fixated. σ_{left} and σ_{right} show the extent of the perceptual span on the left and the right of the gaze location, respectively. α is a free parameter.

For a given reading task, the LDD model assumes that the processing load of a word first increases and then decreases over time[23].The difference in processing load between high- and low-frequency words (shown in red and blue, respectively) is negligible early during the processing but becomes more apparent by about 40 ms or so into the fixation. The processing load of the word decreases, over time, from about 70 ms from the start of the processing and goes to zero earlier for high- than low-frequency words. The maximum processing load is higher for low- than high-frequency words. In addition to word frequency, the processing load is affected by the reading task. Therefore, according to the model, the time that is needed for the processing of a word is affected by its frequency and the reading task.

We assumed that the amplitude of attention (AoA), x ($x \neq 0$) characters from the gaze location would be

[23] This assumption is similar, but not identical, to the assumption of the SWIFT model (e.g., Engbert et al., 2005) . In the SWIFT model, the activation of a word, at lexical levels, increases, over time, until it reaches a threshold and then decreases. The threshold decreases with word frequency.

$$AoA(x, t, \tau, p, \propto) = e^{-(\alpha x^2 LoP(t+p,\tau))/\sigma t} \quad \text{(Equation 2)}$$

where $AoA(x, t, \tau, p, \alpha)$ is the amplitude of attention, x denotes the distance from the gaze location in characters, t shows the time from the beginning of the fixation and p denotes the preview benefit that a word obtains before it is fixated. The amplitudeincreases over time (i.e., attention defocuses). It is smaller for further distances from the gaze location. The maximum amplitude of attention is 1 when attention is completely defocused. $LoP(t + p, \tau)$ denotes the load of the processing of the word at time t from the beginning of the first fixation on the word. For a given task of reading, the load of the processing of a word depends on the amount of preview the word obtains (p). Consequently, the load of the processing of the word, t milliseconds after the beginning of the first fixation on the word, would be $LoP(t + p, \tau)$. The higher the load of the processing of a word is, the smaller the amplitude of attention would be x $(x \neq 0)$ characters from the gaze location. The last parameter is α: a free parameter that was set separately for the task of reading sentences and the task of reading strings of words (with or without valid preview).

For the task of reading sentences, p was set to 50 ms. For the task of reading strings of words, p was set to 40 ms. A slightly smaller p was reasonable for the task of reading strings of words, given that (i) the preview benefit was sufficient to reveal an effect of frequency on the focus of attention early in a fixation, but (ii) the effect of frequency on the focus of attention seemed to be smaller compared to the task of reading sentences. For the task of reading strings of words, with an invalid preview, p was set to 0.

Attention is asymmetric around the gaze; we showed this in the model by σ, where the amount of σ, x characters from the gaze location, depends on whether x is located in the direction of reading.

$$\sigma = \begin{cases} \sigma_{left}, & x < 0 \\ \sigma_{right}, & x > 0 \end{cases}$$

where, $\sigma_{left} < \sigma_{right}$ in reading western texts.

For the task of reading sentences, we set the pair of $(\sigma_{left}, \sigma_{right})$ to $(4, 15)$ characters. This is because the extent of the perceptual span is between 3-5 characters to the left and at most 15 characters to the right of the gaze location in reading sentences (e.g., McConkie & Rayner, 1976).

We did not have an empirical data for the perceptual span for the task of reading strings of words. Given that the perceptual span is positively correlated with the speed of reading, we used the speed of reading to estimate the extent of the perceptual span for the task of reading strings of words. The speed of reading (SoR) reduced almost by a third when the reading task changed form reading sentences (Experiment 1) to reading strings of words (Experiment 4).

$$\frac{SoR(\,reading\ sentences\ =22.25\ characters\ per\ seconds)}{SoR(\,in\ reading\ strings\ of\ words\ with\ a\ valid\ preview=16.94\ characters\ per\ seconds)} = 1.31$$

Thus, we set the pair of $(\sigma_{left}\ ,\ \sigma_{right})$ to $(4\ ,\ 10)$ characters for the task of reading strings of words. The speed of reading dropped by about 10% for the task of reading strings of words with an invalid preview, compared to when preview was valid. Therefore, we set the pair of $(\sigma_{left}\ ,\sigma_{right})$ to $(4$, 9) characters.

We kept the same value of σ_{left} for all reading tasks because (i) the extent of the span on the left side of the gaze location is already small and so any changes would be small and (ii) preview, and as a result the speed of reading, is affected by the extent of the span on the right of the gaze.

Table 1.7 shows the choice of parameters for different types of the reading task in the model. It should be noted that the magnitude of α was smaller for the task of reading strings of words $(\alpha = 0.14)$ than the task of reading sentences $(\alpha = 0.175)$. If the same $\alpha = 0.14$ was used for the task of reading sentences, the pair of $(\sigma_{left}$, $\sigma_{right})$ should have been set to $(3.2\ ,\ 12)$ characters to give us the same results. This is in line with a smaller span on the left side of the gaze location (also suggested in section 7.3.1) but a bigger span on the right side of the gaze location for the task of reading sentences than strings of words (Häikiö et al., 2009; Inhoff et al., 1989).

If the same $(\alpha = 0.14)$ is used for the task of reading sentences and strings of words, the ratio of σ_{right}(reading sentences) / σ_{right}(reading strings of words with valid preview) would be 1.2, which is slightly smaller than the ratio of the speed of reading in the two tasks (i.e., 1.31). This suggests that the size of the perceptual span is not the only factor that affects the speed of reading.

7.4.3 Results from the LDD Model

The bottom panels in Figures 7.1, 7.2 and 7.3 show the model's results for the amplitude of attention 6 characters to the left (solid lines) or right (dashed lines) of the gaze location (i.e., for the spatial offsets of the peripheral probes in our experiments). The results are shown for when the fixated word is high (red lines) or low (blue lines) in frequency, for the task of reading sentences, strings of words or strings of words with an invalid preview, respectively.

The model shows asymmetric attention around the gaze location. The amplitude of attention increases over time, that is, attention defocuses for both reading tasks. This is compatible with the results in Experiments 1, 2, 4 and 5.

For the task of reading sentences, 40 ms from the beginning of the first fixation on a word, the model shows a bigger effect of word frequency on attention on the left than the right side of the gaze. For the task of reading strings of words, when preview is valid and 40 ms into the fixation, the model shows an effect of frequency that is not bigger on the left than the right. This is in line with the results of Experiments 1 and 4. Thus, the model shows that the reading task modulates the frequency effects on attention.

In addition to the reading task, preview modulated the effects of frequency on attention, early in a fixation (results from experiment 4 and 5). For the task of reading strings of words, early in a fixation, (i) attention defocused faster for the valid- than the invalid-preview group, and (ii) the effect of frequency on the focus of attention was only significant for the valid-preview group. The LDD model predicts these findings: Figure 7.2b and 7.3b shows (i) an interaction between preview and frequency and (ii) an interaction between preview and temporal offset.

According to the model, the interaction between preview and temporal offset occurred because, when preview was valid, the load of processing of the word decreased from 10 ms to 40 ms into the fixation. On the other hand, when preview was invalid, the load of processing of the word increased from 10 to 40 ms into the word. Consequently, the defocusing of attention, from 10 ms to 40 ms into the fixation, was slower when preview was invalid.

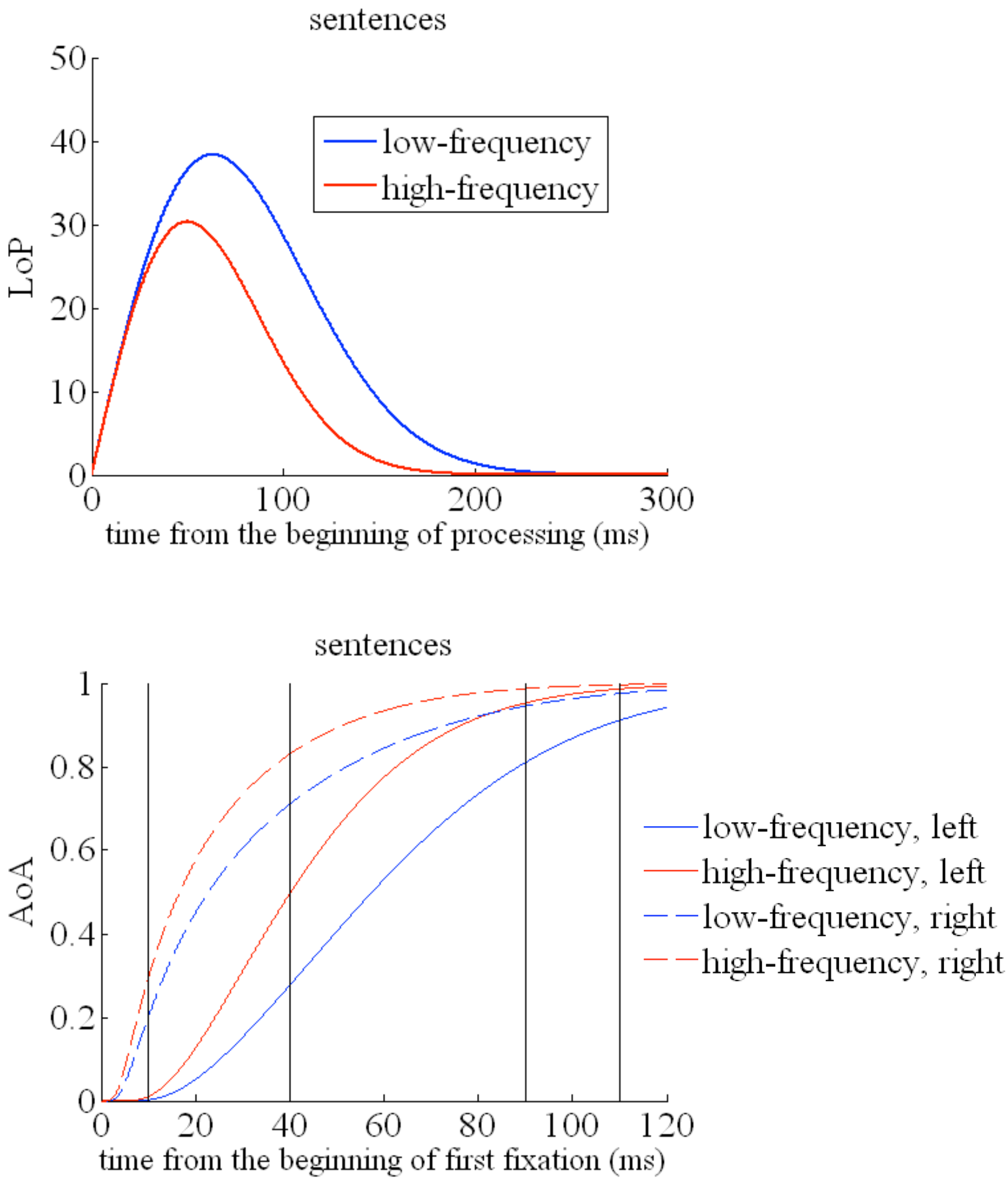

Figure 7.1. The LDD model results for the task of reading sentences. Top panel: the processing load of a word is shown for when the word is low (blue lines) or high (red lines) in frequency. The x-axis shows the time from when processing starts. Bottom panel: the amplitude of the focus of attention 6 characters to the left (solid lines) or to the right (dashed lines) of the gaze location is shown for a high- or low-frequency fixated word. The x-axis shows the time from the beginning of the first fixation on the word. Vertical black lines show the temporal offsets for peripheral probes in Experiments 1 and 2 during the engagement phase.

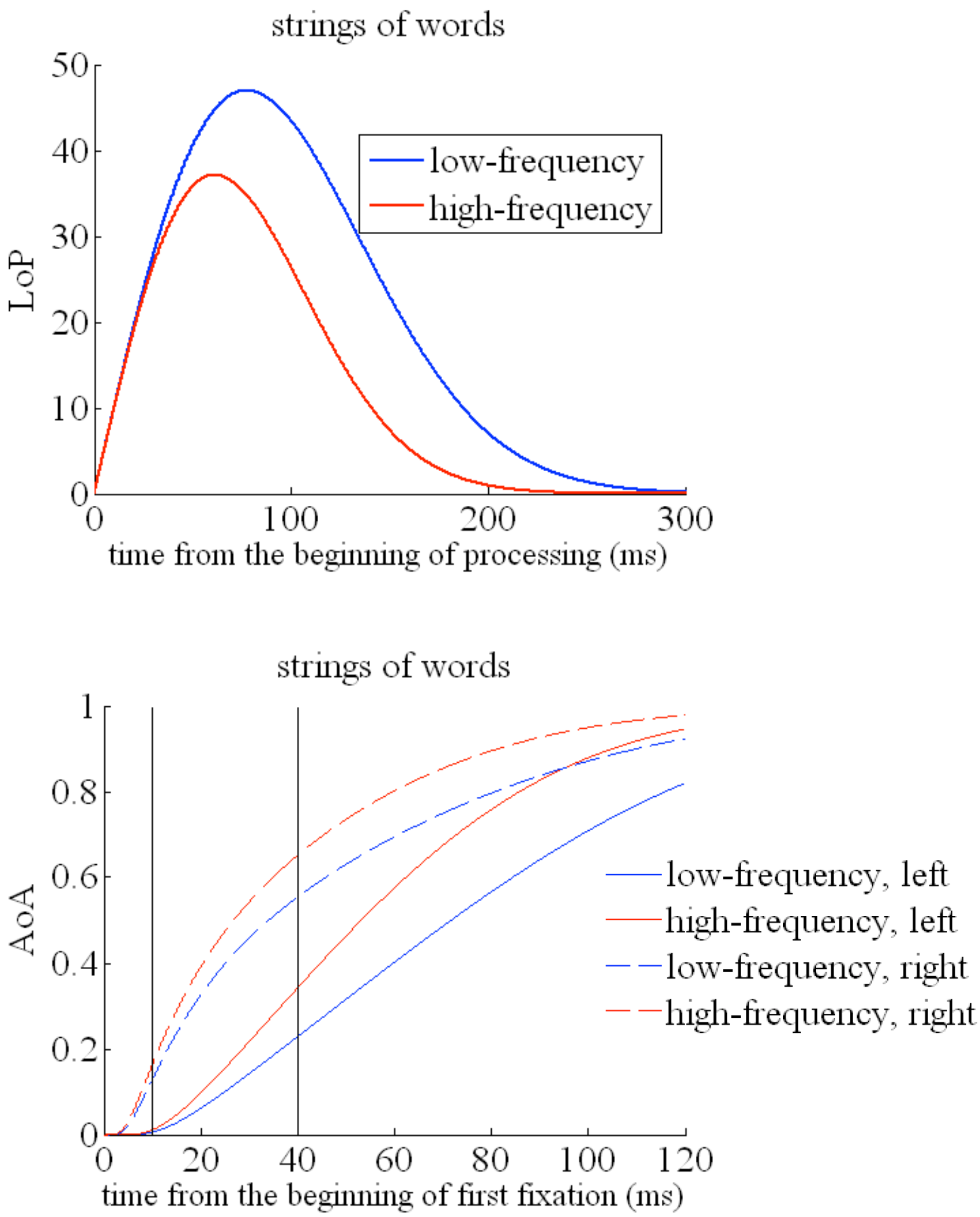

Figure 7.2. The LDD model results for the task of reading strings of words. Top panel: the processing load of a word is shown for when the word is low (blue lines) or high (red lines) in frequency. The x-axis shows the time from when processing starts. Bottom panel: the amplitude of the focus of attention 6 characters to the left (solid lines) or to the right (dashed lines) of the gaze location is shown for a high- or low-frequency fixated word. The x-axis shows the time from the beginning of the first fixation on the word. Vertical black lines show the temporal offsets for peripheral probes in Experiment 4 during the engagement phase.

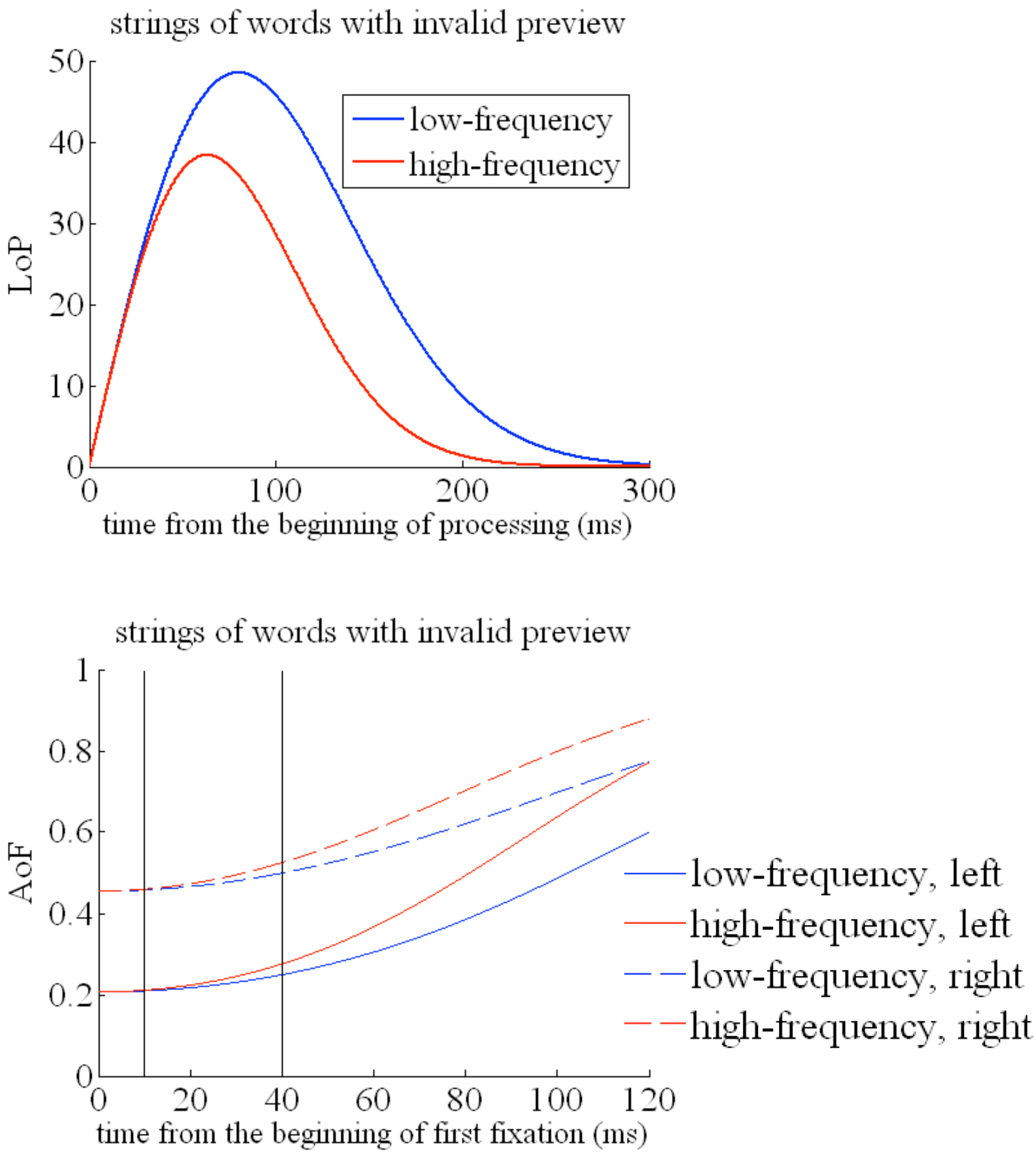

Figure 7.3. The LDD model results for the task of reading strings of words with an invalid preview. Top panel: the processing load of a word is shown for when the word is low (blue lines) or high (red lines) in frequency. The x-axis shows the time from when processing starts. Bottom panel: the amplitude of the focus of attention 6 characters to the left (solid lines) or to the right (dashed lines) of the gaze location is shown for a high- or low-frequency fixated word. The x-axis shows the time from the beginning of the first fixation on the word. Vertical black lines show the temporal offsets for peripheral probes in Experiment 5 during the engagement phase.

Our model replicates our empirical results on the dynamics of attention, during the first half of a fixation, for different levels of word frequency and reading tasks. Given that (i) word recognition needs spatial attention (Waechter et al., 2011) and (ii) attention and the eyes are coupled (e.g., Bryden, 1961; Deubel & Schneider, 1996; Fischer, 1999; Gersch et al., 2004; Hoffman & Subramaniam, 1995; Kowler & Blaser, 1995), models of eye movement control in reading can benefit from incorporating our results, manifested in the LDD model of attention, into their assumptions.

7.5 Contribution to attention research

Models of eye movement control in reading, and in general, can benefit from our results on the dynamics of attention and the LDD model of attention. Most importantly, our work improved the current understand of the dynamics of attention in active reading. Furthermore, we showed an effect of frequency on the focus of attention, early in a fixation; to the best of our knowledge, this has not been reported before in static or active viewing conditions. Our contributions to (i) the perceptual span in reading and (ii) the effects of load on the focus of attention are provided in sections 7.5.1 and 7.5.2, respectively.

7.5.1. The perceptual span in reading

Using the moving-window paradigm, McConkie and Rayner (1975) defined the perceptual span as the region around the gaze from which information that affects eye movement behaviour is extracted; they showed that this region extends further to the right than to the left. Miellet et al. (2009) showed that attention and ongoing processing, but not visual acuity, determine the size of the perceptual span, suggesting that it is an attentional (rather than a visual) span. Consistent with this attentional interpretation, the size of the perceptual span depends on the effective difficulty or load of the text (Inhoff, et al., 1989; Rayner, 1986). For example, it is wider for skilled than for beginning readers (Häikiö, Bertram, Hyönä, & Niemi, 2009). Also, using a boundary technique, Henderson and Ferreira (1990) showed that participants obtained more preview benefit from the upcoming word when the fixated word was high rather than low in frequency. They concluded that the size of the perceptual span is variable and is smaller for low-frequency than for high-frequency words. Note that, although Henderson and Ferreira (1990) did not directly measure the perceptual span, they interpreted their findings as changes in the perceptual span. The common assumption on the perceptual span in the reading literature is that it is variable and is affected by the load of the reading task or the fixated word. However, the extent of the span is usually not considered to vary over the course of a fixation and by implication the amplitude of attention at any one spatial offset is not considered to vary.

We directly measured attention and showed that the amplitude of attention does vary, during the course of a fixation, and that the dynamics of attention are affected by the load of words (Experiments 1-5; Ghahghaei et al., 2013). We believe that our results are (i) applicable to the perceptual span and (ii) in line with, and add to, previous findings regarding it. Our results are in line with the perceptual span and the amplitude of attention at any one spatial offset being (i) asymmetric around the gaze location and (ii) variable, over the course of a fixation and (iii) affected by the moment-to-moment load of the word that is being processed.

The dynamics of the amplitude of attention and the effects of load on these dynamics could not be revealed only by using the moving-window paradigm (McConkie & Rayner, 1975), the boundary paradigm (Rayner, 1975a, 1975b) or disappearing-/masked-text paradigms (Rayner et al., 1981). This is because, in the first two paradigms, display changes occur during a saccade; thus, the timecourse of a given effect cannot be revealed. In the disappearing-/masked-text paradigm, on the other hand, display changes occur during a fixation and, presumably, the effects of the timing of these changes give us some insight into the timecourse of attention. However, (i) these changes affect eye movements only during a crucial time-window (i.e., the first 60 ms) into a fixation and (ii) there is no report of an effect of frequency on the duration of this crucial window. Thus, none of these paradigms can address the dynamics of attention in reading. The version of the dynamic-orienting paradigm (Fischer, 1999) that we used, on the other hand, directly addresses the dynamics of attention in reading and reveals the effects of load on these dynamics (Experiments 1-5; Ghahghaei et al., 2013). Our work shows that the amplitude of attention varies over the course of a fixation and that its dynamics are affected by the load of the task and the fixated target and/or the upcoming one.

7.5.2. Contribution to the perceptual-load literature

The effect of frequency on the focus of attention, during the engagement phase (Experiments 1, 2 and 4), is similar to the effect of the perceptual load of a target stimulus on the focus of attention on the target. In static viewing conditions, attention is more focused on a stimulus when its perceptual load is higher (e.g., Brand-D'Abrescia & Lavie, 2007; Caparos & Linnell, 2009, 2010; Eriksen & Hoffman, 1972, 1973, 1974; Eriksen & St. James, 1986; Kahneman, & Chajczyk, 1983; Lavie, 1994, 1995; Lavie & Tsal, 1994; Linnell & Caparos, 2011; Parks, Hilimire & Corballis, 2011). Using the flanker paradigm, Brand-D'Abrescia and Lavie (2007) showed that the perceptual load of a string of letters was higher (i) for longer strings and (ii) for when the string made a non-word than a word. Madrid et al (2011) showed that the perceptual load of a word is higher when it is presented to the left than right visual field. For both Brand-D'Abrescia and Lavie's (2007) and Madrid et al.'s (2011) studies, attention was focused on a word more when its perceptual load was higher. To the best of our knowledge, there is no report, other than our results (Ghahghaei et al., 2013), that shows an effect of frequency on the focus of attention in static or active viewing conditions.

Our results on the effects of word frequency and preview on the focus of attention suggest that the perceptual load of a word is variable over time and depends on the stage of the processing of the word. This variable load in turn affects the dynamics of attention. In active reading, as early as 40 ms into a fixation on a word, our results suggest that the perceptual load of a word is higher when its frequency is lower, but only if sufficient preview has been obtained for the word. Thus, early in a fixation, attention was more focused on the gaze, for low- than high-frequency words, only when preview was valid.

We propose that the frequency of a word affects its perceptual load (i) only when its processing has reached those levels that correspond to frequency and (ii) before the meaning of the word is accessed. This is because, after the meaning is accessed, the perceptual resources that were presumably committed to processing the word should be released. In other words, we suggest that there is a limited time-window within which there is an effect of a word's frequency on its perceptual load.

7.6 Future directions

We foresee two horizons for the future direction of this study. The first horizon is to further investigate the dynamics of attention in normal readers; this is discussed in section 7.6.1. The second horizon is the significance of our findings in clinical studies; this is discussed in section 7.6.2.

7.6.1 Future experiments

Our probe technique was sensitive not only to the frequency of the fixated word but also to the orthographic familiarity of the first trigram in the upcoming word. This suggests that our technique can reveal (i) the effects of the processing load of the fixated word *and* the upcoming word on attention, and (ii) the effects of different processing loads, for example, those manipulated by frequency or orthographic familiarity.

We showed an effect of the processing load of more than one word on attention: the load of the fixated word and the upcoming word, early *and* late in a fixation, respectively. Parallel models of eye movement control in reading assume that more than one word can be processed in parallel at lexical levels (e.g., Engbert et al., 2005, SWIFT model); whereas, serial models (e.g., Reichle et al. 1998, the E-Z Reader model) assume that only one word can be processed at lexical levels at a time. If more than one word can be processed at lexical levels, it should be possible to see the effects of the lexical load of more than one word on attention at least at some points during a fixation. To investigate this, further studies are needed where the lexical load of at least two adjacent words are manipulated, for example, the frequency of the fixated word and the upcoming word. An effect of the frequency of more than one word on attention would support the parallel models of eye movement control in reading. Furthermore, follow up experiments where (i) the load of the fixated word and the next word are manipulated and (ii) more spatial and temporal offsets are used for the probe would help us better understand the dynamics of attention and the effects of load on attention. Specifically, employing more spatial offsets for peripheral probes during the engagement phase, would help us better understand whether (i) the amplitude of attention (ii) or the extent of the focus of attention (iii) or both increase during the engagement phase.

In addition to revealing the effects of the load of the fixated word *and* the upcoming word, our technique revealed the effects of different load manipulations (frequency and orthographic familiarity of first trigrams) on attention. Thus, our technique can be used to look at the timecourse of different kinds of load in reading. The effects of different load manipulations on the perceptual span have been investigated (e.g., Henderson & Ferreira, 1990). The timecourse of these load effects, however, was not clear. Our results, on the other hand, showed that the span is wider on the right side of the gaze for high- than low-frequency words both early and late in a fixation. In terms of manipulating the orthographic familiarity of first trigrams in the upcoming word, our results showed that their familiarity affects attention shortly before the saccade to the word.

We think that our technique can be used to reveal the timecourse of other kinds of load. For example, assume that the load of the words is manipulated by manipulating how syntactically easy/difficult processing of the words are, as in Henderson and Ferreira’s (1990) study. If accessing the meaning of a word is affected by post-lexical processing (e.g., whether the words fit into the sentence), then we would expect an effect of this load manipulation on the focus of attention, and consequently, on the orienting of attention. On the other hand, if this load manipulation only affects the decision on the timing to move the eyes to the next word, we would expect to see an effect of this load manipulation only on the orienting of attention.

Although we did not look at the effects of word boundaries on attention in the current work, our method has the potential to address this by including probes with small (e.g., 3 characters) or big (e.g., 9 characters) spatial offsets from the gaze location.

In sum, our results and our technique add to the current understanding of attention and the effects of load in normal readers. In section 7.6.2, the significance of our findings for abnormal reading in dyslexia is discussed.

7.6.2 Clinical significance

Reading is a more demanding task for dyslexic than normal readers as indexed by shorter, and more regressive, saccades and longer fixations (Ashby et al., 2005; Rayner, 1998). Given that (i) attention is first focused on the gaze and then orients towards the next saccadic target, in normal readers (Experiments 1-5; Ghahghaei et al., 2013), and (ii) attention is necessary for word recognition (Waechter et al., 2011), any deficits in attentional focusing and/or orienting mechanisms may impair reading. Thus, results support those studies that assume visual attentional deficits independent of phonological deficits in dyslexia (for review see Valdois, Bosse, &Tainturier, 2004; Bellocchi et al., 2013).

It has been suggested that part of the problem in dyslexic readers comes from deficits in attentional mechanisms. Geiger et al. (1992) showed that, under static viewing condition, dyslexic children were abnormally good at processing eccentrically (between 2.5 and 10 visual degrees) located letters in the visual field that were in the direction of reading (right for English readers, left for Hebrew readers) while they simultaneously identified a target letter at the fixation location. The authors concluded a difficulty in focusing attention for dyslexic readers. In another study, dyslexics also showed deficits in the orienting of attention. In a visuo-spatial orienting paradigm, using an event-related potentials (ERPs) measure, Dhar et al. (2008) showed that the cortical response to peripheral cues was diminished in dyslexic compared to normal readers, suggesting a weaker voluntary orienting of attention in dyslexics (Buchholz & Davies, 2007; Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000; Franceschini, Gori, Ruffino, Pedrolli & Facoetti, 2012). Thus, deficits in focusing and orienting attention are reported in dyslexics. However, studies on correlations between attentional deficits and the abnormal reading in dyslexics are mostly conducted in non-reading situations (e.g., Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012).

Rayner, Murphy, Henderson and Pollatsek (1989) addressed the size of the perceptual span in a reading task for a dyslexic participant, SJ, using a moving-window paradigm. They showed that the size of the window for which SJ's speed of reading was as fast as his normal speed of reading (a window of 23 characters, 11 characters on each side of the gaze location; Figure 7.4) was smaller than the size of the corresponding window for five control subjects with the same gender, profession and age as SJ (a window of 31 characters, 15 characters on each side of the gaze; Figure 7.4). Thus, the perceptual span was narrower for SJ than normal readers. Interestingly, SJ's speed of reading increased compared to his normal speed when the window was 15 characters (i.e., 7 characters to the left and 7 characters to the right of the gaze location) or smaller and letters outside the window were masked by 'X's (rather than by random letters). The authors reasoned that, in SJ's case, the letters from the parafoveal region interfered with reading. A smaller window with no information from the parafovea blocked this interference and, thus, improved his reading rate.

Our results can explain why the speed of reading increased when the window size decreased for SJ. We showed that attention is first focused on the gaze, when presumably the fixated word is processed (Ghahghaei et al., 2013). Given that deficits in focusing attention is reported in dyslexics (Geiger et al., 1992), we infer that a part of the problem in SJ's case (Rayner et al., 1989) was an impairment in focusing attention; when attention was artificially focused, in a moving-window paradigm, reading improved. Thus, focused attention may be crucial for reading, for example, to increase the signal to noise ratio. The need for focused attention, early in a fixation, is supported by the results of the disappearing/masked text paradigm where, for normal reader, the availability of visual information from the fixated word is crucial for reading during the first 60 ms or so of a fixation (e.g., Rayner et al., 2003, 2006). This critical time may be longer for dyslexics whose ability to focus attention is impaired, resulting in longer fixations. Furthermore, given the deficits in focusing and orienting of attention in dyslexics, it could be more challenging for dyslexic than normal readers to (i) select the next saccadic target and/or (ii) preview the upcoming word, resulting in further impairment to reading. Our work, for the first time, shows the timecourse of attentional focusing and orienting in normal reading and can be used as a baseline to study how attentional deficits may directly affect saccade programming and/or the flow of information processing during reading.

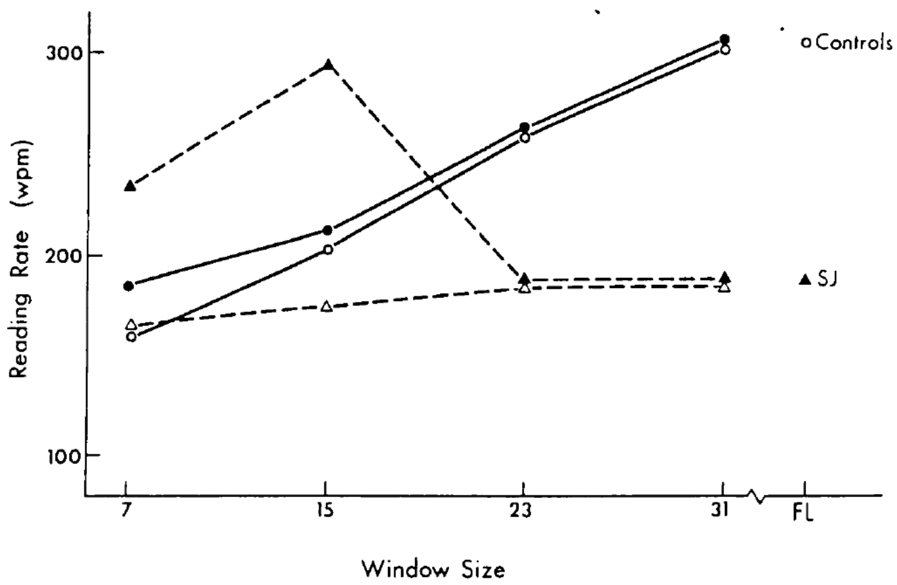

Figure 7.4. Reading rate (in words per minute) as a function of window size (in characters) for SJ and the control participants. The dashed lines represent SJ and the solid lines represent the controls. Open symbols are for the case where letters outside the window were replaced by random letters; filled symbols are for the case where letters outside the window were replaced by 'X's. FL represents 'Full Length'; that is, reading with no moving-window paradigm. From Figure 1 in Rayner et al., 1989.

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