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UNIVERSITY OF SOUTHAMPTON

FACULTY OF SOCIAL, HUMAN AND MATHEMATICAL SCIENCES

Psychology

Volume 1 of 1

Binocular Vision in Reading

by

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ABSTRACT

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BINOCULAR VISION IN READING

Mirela Petrova Nikolova

Binocularity is a fundamental characteristic of human visual function. It plays an important part for a crucial socially acquired complex psychological skill: reading. A large number of studies have been dedicated to the exploration of binocular vision, its underlying physiological and neural mechanisms, its role in depth perception and stereopsis, and its pathology and treatment. Similarly, a vast and detailed literature has been devoted to the empirical investigation of oculomotor control during reading and the cognitive processes associated with written language comprehension. There are, however, surprisingly few examples of studies that have considered the role of binocular vision in relation to written text processing. Thus, the mechanisms via which binocularity influences the decisions of when and where to move the eyes in reading have remained largely unspecified. The aim of this thesis is to address these limitations by presenting three empirical papers which investigate the intricate relationship between binocular vision, oculomotor control and cognitive processing during reading. The documented experiments have 1) considered the role of vertical motor and sensory fusion during word identification, 2) explored binocular advantages in reading and 3) investigated the mechanisms via which binocular vision influences processing of foveal and parafoveal text. Overall, the empirical work presented in this thesis brings the field a step closer to bridging the gap between the existing understanding of human binocular vision and the conscious visual experience of a fused, unified binocular percept upon which written language comprehension is fundamentally based.

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I, …… [please print name]

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[title of thesis] ………

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3. Where I have consulted the published work of others, this is always clearly attributed;
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Chapter 1: Introduction

1.1 General Introduction

The human visual system is organised around a pair of frontally placed horizontally separated visual receptors. The adaptive significance of this particular arrangement of the eyes has been debated widely within the field of anthropology (Heesy, 2009). For example, Collins (1921) proposed the arboreal locomotion theory and was the first to suggest that binocular vision in primates was required in order to accurately judge distance between arboreal substrates, particularly during leaping, manoeuvring through branches and nocturnal vertical clinging. In contrast, Cartmill (1972) proposed the opposing visual predation hypothesis, according to which traits of the primate binocular visual system could be explained by visual predation habits, such as finding food in the forest canopy and undergrowth, particularly in conditions of reduced light. Although the debate between proponents of both theories is still ongoing, it is widely agreed that the development of high-precision binocular vision was of prime importance for the survival of the species.

The present thesis focuses on the role of this fundamental characteristic of the human visual system for an important, socially acquired psychological skill: reading. Reading is a complex and uniquely human ability and is extremely useful in today's highly technological modern society. It requires the rapid, synchronised operation of visual, neuropsychological and cognitive processes. The ability to read is closely related with academic achievement, employment prospects, self-esteem and overall life satisfaction (Reynolds, Wheldall, & Madelaine, 2010). Therefore, the scientific exploration of processes related to reading is highly valuable for the understanding of all those interrelated contributing systems.

The key subject of this thesis thesis is the role of binocular vision for written text processing in English. The following sections will firstly consider eye movement behaviour in reading and how it relates to on-going cognitive processes underlying language comprehension. Then, major findings in the field of binocular vision will be reviewed, with a focus on areas of research relevant to the understanding of how a single unified high-resolution percept of the visual environment is obtained from two separate visual inputs. The final section of the introductory chapter will explore the role of binocular vision in reading, focusing on several lines of research that have been examined in recent years, and that will be the focus of the following empirical chapters.

1.2 Eye Movement Research in Reading

Over the past five decades, researchers interested in reading have accumulated a wide range of findings regarding various underlying visual and cognitive processes. Eye tracking has been of particular interest as a research methodology, because eye movements are the behavioural manifestation of on-going cognitive processes during reading (Liversedge & Findlay, 2000; Rayner, 2009). Eye movement behaviour during reading is characterised by a sequence of saccades, which are rapid ballistic movements of the two eyes in the same direction (conjugate movements). Saccades are characterised by a consistent relationship between several parameters: speed (velocity), size (amplitude) and duration. That is, there is a strong correlation between these parameters in the saccadic eye movements of individuals with normal vision.

During reading, saccades are typically followed by brief periods of relative stillness known as fixations. This staccato behavior is necessitated by the physiological make-up of the retina, and the resulting acuity limitations for the visual system. Visual acuity is highest in the foveal area, situated approximately at the centre of the macular retinal region and corresponding to the central 2% of the visual field (Balota & Rayner, 1991). This area contains the largest concentration of cone photoreceptors in the retina and is responsible for high-resolution colour vision. Beyond the fovea, in the parafovea and the periphery, the number of cone photoreceptors decreases and visual acuity drops precipitously, which makes it extremely difficult to perceive highly detailed information (Rayner & Bertera, 1979). Consequently, the oculomotor system continuously orients the eyes in such a way that light reflected off objects of interest falls within the fovea. In other words, fixations and saccades during reading ensure the sequential intake of sufficient high-quality visual information for successful language processing and comprehension. It is important to note that because saccadic eye movements are optimized for speed, their execution results in considerable motion blur of the perceived image. Saccadic suppression, or masking of the blurred retinal percept, is required for the maintenance of a stable perceptual representation of the visual environment (Burr, 2004). This illustrates a fundamental aspect of reading behaviour: even though the intake of visual information is largely restricted to fixations, visual and lexical processing are not disrupted by the movement of the eyes (Irwin, 1998).

1.2.1 Commonly reported eye movement measures

One of the strengths of eye movement methodology is that it can be used to obtain a moment-to-moment index of on-going cognitive processes associated with individual word recognition and global text comprehension (Liversedge & Findlay, 2000). This distinguishes eye movement measures from traditional behavioural measures, such as reaction time and accuracy, which can only provide an indication of duration or performance at a single time point, typically at the end of a trial. In contrast, eye movement recordings can be used to measure the ongoing temporal processing associated with a unit of text.

Typically, researchers analyse a set of first-pass (early) and second-pass (late) measures. First-pass measures represent initial reading, consisting of the first set of forward fixations, and excluding regressions back into the text. They can be informative with respect to variables that influence initial access to representations of a word's orthography, phonology or semantics. Second-pass measures represent rereading of a single word or a larger region of interest, and can be informative for examining influences on later processing (e.g. semantic factors). Table 1 below contains a list of the most commonly reported measures used to estimate word recognition processes in eye movement studies.

Table 1. Dependent measures typically reported in eye movement experiments examining word recognition processes. Adapted from Juhasz & Pollatsek (2010).

Early Processing Measures	
Skipping probability	The probability that a word will not receive a direct fixation during first-pass reading.
First fixation duration	The duration of the very first fixation on a word, regardless of whether the word has been fixated more than once.
ingle fixation duration	The duration of a fixation when the reader made exactly one fixation on the word during first-pass reading.
Gaze duration	The sum of all first-pass fixations on a word during first-pass reading, prior to the eyes moving away from the word in either direction.
Late Processing Measures	
Go-past time	The accumulated time from when a reader first fixated on a word until their first fixation to the right of the target word, including any regressions made before moving forward past the word.
Second pass duration	The amount of time spent re-reading a word after first-pass reading.
Regression rate	The percentage of regressions into a target word (regressions in), or out of a target word (regressions out).
Total reading time	The sum of all fixations made on the words, regardless of whether they were made during first- or second-pass reading.

1.2.2 Eye movement control and cognitive processing in reading

Over the past several decades, two important questions have been at the heart of eye movement research during reading: when and where do the eyes move when we process written text. These questions have been central for the development of some of the most influential computational models of eye movement control during reading, which make different assumptions about the extent to which foveal (directly fixated) and parafoveal (outside the point of fixation) information is processed as a reader's eyes move along a piece of text. Briefly, according to sequential attention shift (SAS) models, such as the influential E-Z Reader model (Reichle, Rayner, & Pollatsek, 2003; Reichle, Pollatsek, Fisher, & Rayner, 1998; see Reichle, 2011, for review), language processing in reading occurs in a serial fashion, such that each word in a sentence will only be fixated after the preceding word has been identified. Within the serial processing architecture, some features of the text to the right of fixation can be extracted parafoveally for the purpose of saccade targeting and facilitated word recognition once the parafoveal word is fixated. This assumption contradicts guidance by attentional gradient (GAG) models, such as SWIFT (Engbert, Longtin, & Kliegl, 2002; Engbert & Kliegl, 2011). According to GAG models, cognitive processing resources are distributed across the effective visual field, making possible the parallel processing of several words.

A comprehensive review of the existing computational models of oculomotor control in reading is beyond the scope of this thesis, though such reviews have been provided elsewhere (see Reichle, Rayner, & Pollatsek, 2003; Reilly & O'Regan, 1998). Nevertheless, it is clear that factors affecting the decision of where and when the eyes move have important implications not only for the endeavour to model human eye movement behaviour, but also for the understanding of the cognitive processes that underlie written language comprehension. Characteristics of the text that influence each of these decisions will be discussed in detail in the following sections.

A large body of research has been dedicated to exploring when the eyes move in reading, or in other words, what factors affect the speed and efficiency with which foveal processing can take place. Empirical findings have revealed that fixation times on a word vary as a function of features such as word length, orthographic, phonological and morphemic coding, as well as linguistic characteristics (e.g. word frequency), semantic qualities and contextual predictability (see Hyönä, 2011, for review). For example, it is well-established that fixation times are longer on long words than on short words (Barton, Hanif, Eklinder Björnström, & Hills, 2014; Hyona & Olson, 1995; McDonald, 2006). One likely reason for that effect is that processing of longer words may suffer from the drop-off in visual acuity outside the fovea, thereby resulting in lower efficiency of word identification (Aghababian & Nazir, 2000). This in turn may necessitate multiple fixations, which would ultimately result in inflated processing times.

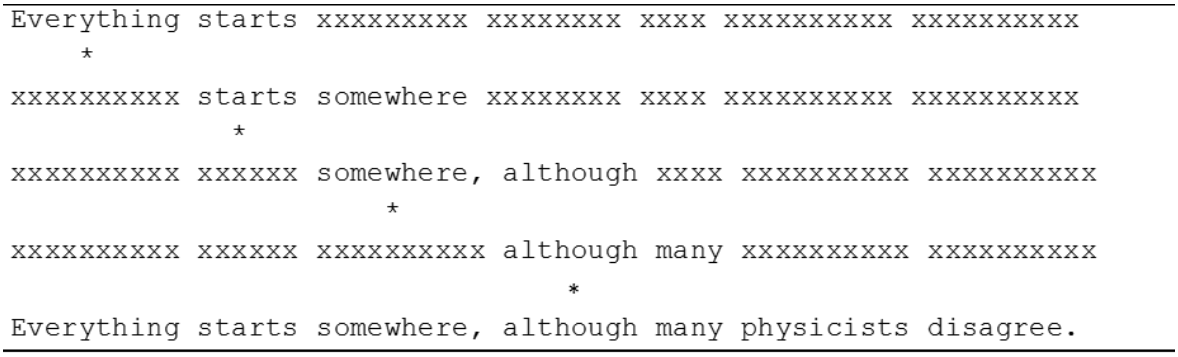
With respect to linguistic influences on foveal processing times, the word frequency effect is among the most well-documented and robust findings in eye movement research (Henderson & Ferreira, 1990; Inhoff & Rayner, 1986; Rayner & Duffy, 1986; White, 2008). The more frequently a word occurs in the language (i.e. the higher its lexical frequency), the less time is needed to identify it. In contrast, if a word does not occur frequently (i.e. its lexical frequency is low), its processing is associated with a higher cognitive load, and therefore, inflated fixation durations. Further evidence for the importance of word frequency information for foveal processing was presented in a series of disappearing text studies (Liversedge, Rayner, While, Vergilino-Perez, Findlay, & Kentridge, 2004; Rayner, Liversedge, White, & Vergilino-Perez, 2003). These experiments employed a gaze-contingent technique such that during sentence reading, each word was only available for 60ms after fixation onset. Afterwards, the words were either masked, or they disappeared. The researchers reported several important findings regarding the impact of visual and linguistic factors on oculomotor control: (1) in masked/disappearing text conditions, reading proceeded without interruption, implying that 60ms is sufficient for the visual system to take in information required for word processing. (2) Even after the fixated words disappeared, fixation durations on the blank space were determined by the target word’s length and frequency, analogous to normal reading. The experiments demonstrated that on-going cognitive processes associated with the text play a central role in eye movement control during reading by informing the decision of when to move the eyes.

Overall, the above findings have provided largely uncontroversial evidence that a multitude of characteristics associated with the fixated word influence the speed with which it is processed. Importantly, however, research has shown that recognising a word is not the only process that readers engage in while fixating it. In fact, during normal reading, a considerable proportion of the average fixation duration is spent planning and programming a saccade to the next point of interest in the text (typically, the following word). It is accepted that a saccade in reading takes approximately 150 ms to plan (Pollatsek, Reichle, & Rayner, 2006). There are two important points to make with respect to saccade planning and execution during reading. Firstly, saccades are ballistic movements, which means that, once initiated, they can no longer be cancelled, nor can their amplitude, direction or intended target be altered. Thus, the most efficient strategy for the oculomotor system during reading is to continuously select the most appropriate saccade targets in order to minimise the rate of corrective saccades that will need to be executed if that target is missed. Secondly, such accurate targeting means that the reader needs to attend to upcoming text prior to directly fixating it in order to determine the optimal target. In other words, during normal reading, extracting information from the parafovea is necessary in order for the eyes to move forward in the text (Hyönä, Bertram, & Pollatsek, 2004; Rayner, 1998). It is therefore important to consider two critical issues with respect to the decision of where to move the eyes in reading. Firsty, how are saccade targets selected. Secondly, what information is attended to in the parafovea, and to what extent is that information processed.

Early research by McConkie and Rayner (1975, 1976) and Rayner (1975) examined the extent to which information from upcoming, unfixated text can be obtained during a single reading fixation. They developed and used the moving window paradigm. This is a gaze-contingent display change technique where a “window” of text with varying size is presented on a computer screen and information beyond it is masked. The window moves on a fixation-to-fixation basis, so that equivalent amounts of unmasked text are available on each fixation (see Table 2).

The moving window paradigm has been employed repeatedly in eye movement experiments in order to investigate the size of the perceptual span, or the amount of linguistic information that is attended to during a single fixation (see Rayner, 1998 for review). Such studies indicate that for skilled adult readers the effective visual field in alphabetical languages such as English extends asymmetrically from 3-4 characters to the left of fixation to 14-15 characters to the right. More recent findings have further suggested that, with relation to word units rather than characters, readers process information from about the beginning of the fixated word to about two words to the right of fixation (Rayner, Castelhano, & Yang, 2009; Rayner, Slattery, & Belangér, 2010).

Table 2. Example of the gaze-contingent moving window paradigm developed by McConkie & Rayner (1975, 1976). The example shows a two-word window, with characters outside it masked by Xs. The asterisk represents fixation position. The control sentence (without a window) is on the bottom.



```
Everything starts xxxxxxxxx xxxxxxxx xxxx xxxxxxxxxx xxxxxxxxxx
    *
xxxxxxxxxx starts somewhere xxxxxxxx xxxx xxxxxxxxxx xxxxxxxxxx
             *
xxxxxxxxxx xxxxxx somewhere, although xxxx xxxxxxxxxx xxxxxxxxxx
                      *
xxxxxxxxxx xxxxxx xxxxxxxxxx although many xxxxxxxxxx xxxxxxxxxx
                                 *
Everything starts somewhere, although many physicists disagree.
```

One crucial finding regarding the perceptual span concerns its size and direction in languages other than English, where the writing systems or the direction of reading differ considerably. For example, in Hebrew, which is read from right to left, the perceptual span extends further to the left than to the right (Pollatsek, Bolozky, Well, & Rayner, 1981). Similar findings were made for readers of Arabic (Jordan et al., 2014) and Urdu (Paterson et al., 2014). Another interesting example is Chinese, a non-spaced, visually dense character-based language, where the perceptual span extends from about one character to the left of fixation to about 3 characters to the right (Inhoff & Liu, 1998). While a direct comparison may give the impression that readers of some languages extract less information from the text than readers of other languages, the spans are equivalent when taking into consideration number of words, rather than number of character spaces. The critical point to make is that the perceptual span is defined by the particular processing demands associated with each orthographic system.

Notably, Rayner (1986) postulated that the perceptual span is attentionally constrained, , meaning that the amount of parafoveal information readers can extract varies as a function of foveal processing difficulty (see also Henderson & Ferreira, 1990; Kennison & Clifton, 1995). More recent work by Miellet, O'Donnell and Sereno (2009) provided further support for that account. The authors implemented a parafoveal magnification (PM) paradigm, whereby information in the parafovea was magnified during each fixation in order to compensate for the decrease of visual acuity outside of the fovea. They demonstrated that the perceptual span was not affected by PM, thus confirming that the amount of information processed during each fixation is primarily affected by cognitive and attentional constraints, rather than visual acuity limitations.

Given the undisputed findings that information to the right of fixation is not only available for processing, but also necessary for fluent reading, it is important to consider the extent to which that information is utilised. In order to explore that question, researchers developed a technique known as the boundary paradigm (Rayner, 1975), illustrated in Table 3 below.

Table 3. Illustration of the invisible boundary paradigm (Rayner, 1975). The asterisk represents fixation position. The manipulation of the word "faster" is only available in the parafovea, prior to direct fixation.

```
Light thinks it travels | bvzter than anything, but it is wrong.
                   *
Light thinks it travels | faster than anything, but it is wrong.
                            *
```

This is a gaze-contingent display change technique, where an invisible boundary is set in a sentence, usually preceding the empty space before a target word. On first-pass reading, the target word is manipulated in some way, such that an incorrect preview is available prior to fixating it. This manipulation is only available parafoveally: as soon as the eyes cross the invisible boundary, a rapid display change occurs, replacing the preview with the original target word. Because of the aforementioned phenomenon of saccadic suppression, the display change typically remains unnoticed, though it can occasionally be detected in cases where the eyes are very close to the invalid preview on the fixation prior to the change (Slattery, Angele, & Rayner, 2011).

The boundary paradigm is among the most widely used experimental techniques in eye movement research (Schotter et al., 2012) because it allows for an investigation of parafoveal processing. Using this technique, researchers have demonstrated that if a word is readily available in the parafovea, fixation times on that word decrease once it is directly fixated, in contrast to when it is not available, or an incorrect preview is presented instead. This finding is known as the parafoveal *preview benefit effect*, and is a very robust finding in eye movement research (Rayner, 1998; Rayner and Pollatsek, 1987; 2009; Schotter et al. 2012; Vasilev & Angele, 2016). The preview benefit effect provides additional evidence of the importance of parafoveal processing for fluent reading. The following sections consider in more detail what type of information is attended to in the parafovea, and for what purpose it is used.

It has been established that different features of the parafoveal word can be extracted prior to directly fixating on it. For example, readers can obtain and utilise information about parafoveal word length to guide their eye movements (Inhoff, Liu, Starr, & Wang, 1998; Juhasz, White, Liversedge, & Rayner, 2008; White, Rayner, & Liversedge, 2005). The importance of word length cues is related to the fact that in English and other similar languages, words units are visually salient, because they are separated by spaces. Word spacing information is used by readers to aid the selection of the next saccadic target. For example, Perea and Acha (2009) showed that if spaces in words were filled in with the letter *x* (e.g. *onexword*), or if they were removed altogether (e.g. *oneword*), reading was considerably slower and readers made more regressions, in comparison to when words were presented normally (e.g. *one word*). One important role of word length and word spacing information is that they can be used to segment the text so that the eyes are systematically guided to a position slightly left of the word centre, known as the *preferred viewing location (*Dunn-Rankin, 1978; McConkie, Kerr, Reddix, & Zola, 1988; Rayner, 1979; Vitu, O'Regan, & Mittau, 1990). This is the most frequently observed landing position during sentence reading, and it has been shown to facilitate word identification by allowing for the largest amount of orthographic information to be made available for foveal processing.

As a point of interest, the importance of word length and word spacing information for eye movement guidance is not necessarily universal across languages. For example, in Chinese, individual characters are not separated by spaces, and there is often ambiguity and disagreement between readers as to the number of words in a sentence (Bai, Yan, Liversedge, Zang, & Rayner, 2008; Hoosain, 1992). With respect to eye guidance, studies have shown that inserting spaces between word boundaries in Chinese text does not produce a benefit in reading performance for skilled adult readers. Additionally, when spaces are inserted either between individual characters, or in such a way as to segment the text into character combinations that produce non-words, reading is disrupted (Bai et a., 2008). What these findings suggest is that there are cases where readers do not make use of orthographic cues related to spacing to segment parafoveal text into word units. In fact, eye movement guidance in Chinese is a fascinating example of the way in which a language’s writing system can influence reading (Perfetti & Harris, 2013) and is the subject of continued empirical investigation (see Li, Liu & Rayner, 2011; Yan, Kliegl, Richter, Nuthmann, & Shu, 2010; Zang, Liang, Bai, Yan, & Liversedge, 2012).

Despite the special case of Chinese**,** research findings have undoubtedly demonstrated the importance of parafoveal cues related to word length and inter-word spacing for eye movement guidance in English and similar alphabetic languages. To be clear, the decision of where to move the eyes is to a significant degree determined by these two characteristics of parafoveal text, at least in languages where spaces are used to clearly mark individual words. There is, however, another key function for parafoveal information during reading. Aside from guiding the eyes, it can also be used to influence processing times during direct fixation. What this means is that information extracted from the parafovea is used to initiate the processing of the upcoming word before it is directly fixated. This can occur through means of trans-saccadic integration of information – to the extent that a preview and a target are similar, information from the preview can be used to partially activate the representation of the target, potentially by narrowing down the number of lexical candidates (Pollatsek, Lesch, Morris, & Rayner, 1992; Rayner, 1975).

Several studies across many different languages have yielded findings compatible with the idea that different types of word characteristics can be integrated across fixations to facilitate word recognition. For example, readers are able to obtain information about the orthographic structure of the upcoming word from parafoveal vision (Häikiö, Bertram, Hyönä, & Niemi, 2009; Henderson & Ferreira, 1990; Rayner, McConkie, & Zola, 1980). Preview benefits can also be obtained when the preview is a homophone (i.e. with the same phonological structure as the target, Ashby & Rayner, 2004; Miellet & Sparrow, 2004; Pollatsek, Lesch, Morris, & Rayner, 1992). Both orthographic and phonological information are believed to influence processing times by facilitating the activation of the lexical entry for the upcoming word (Schotter et al., 2012).

The evidence for lexical, syntactic and semantic preview benefit effects is mixed, with some studies finding no processing facilitation for semantically related previews (see Rayner, Ballota, & Pollatsek, 1986; Rayner, Schotter, & Drieghe, 2014 for studies in English), and others reporting semantic preview benefit effects (see Hohenstein & Kliegl, 2014; Hohenstein, Laubrock, & Kliegl, 2010 for studies in German; Yan, Richter, Shu, & Kliegl, 2009; Yan, Zhou, Shu, & Kliegl, 2012; Yang, 2013 for studies in Chinese). Recent studies in English by Schotter (2013), Schotter, Lee, Reiderman, and Rayner (2015), Schotter and Jia (2016) and Veldre and Andrews (2016) provided evidence for semantic and plausibility preview benefit effects, suggesting that, at least to some extent, readers are also able to extract meaning from the parafovea. These effects can be explained by means of trans-saccadic integration at a local level, whereby similarity in meaning between preview and target results in facilitation of the target’s lexical entry. It can also be explained by integration of meaning at a global, context level, where previews that fit into the global sentence context produce a benefit for processing times. Regardless of the precise mechanism of the effect, however, these research findings suggest that parafoveal processing may potentially be used to extract not only pre-lexical, but also – at least to some extent – post-lexical information about upcoming words in the sentence.

Critically, the importance of parafoveal processing for fluent reading was compellingly demonstrated by Rayner, Liversedge and White (2006), who designed a variation of their earlier disappearing text experiments in which either the currently fixated word or the following word disappeared or was masked shortly after fixation onset. Rayner and colleagues replicated the findings of uninterrupted reading for disappearing foveal words from their previous work (Liversedge et al., 2004; Rayner et al., 2003), and observed an additional intriguing result. When the parafoveal word was unavailable during fixation on the preceding word, reading was significantly disrupted. Readers were unable to make use of information to the right of fixation for saccade targeting purposes, or for the purposes of integrating information between preview and target across saccades. The conclusion was that parafoveal information is of prime importance for uninterrupted reading, and depriving readers of the ability to use it results in considerable cost to their processing of the text.

To summarise, this section has provided an overview of research aimed at answering the two most central questions with respect to eye movement control during reading: *where* and *when* to move the eyes. Previous work has considered a multitude of factors that influence these decisions across different languages: visual and orthographic characteristics of the text, phonological structure, lexical, semantic and contextual qualities. Using a combination of eye tracking and a variety of gaze-contingent display change techniques (e.g. moving window, parafoveal magnification, boundary paradigms) researchers have been able to gain unique insight into the complex, moment-to-moment cognitive processes that take place during the seemingly effortless task of reading a unit of text.

Importantly, however, the overwhelming majority of the above research has used eye movement recordings taken from only one of the eyes (Kirkby, White, & Blythe, 2012). That is, most of what we know about eye movement guidance and information processing prior to and during direct fixation is based on findings that do not consider a fundamental characteristic of the human visual system: binocularity. While this is no reason to doubt the veracity of the existing findings (since reading was typically binocular, even if recording was monocular), it nevertheless poses several interesting questions. First and foremost, what is the role of binocular vision for the different oculomotor and cognitive processes that are involved in reading? Does binocularity influence the ability to encode and comprehend written text? How does binocular vision affect the decision of where and when to move the eyes, or the extent to which foveal and parafoveal text is processed? The following sections focus on the importance of binocular vision and its involvement in high-precision tasks, such as reading.

1.3 From Two Eyes to a Single Percept: An Introduction to Binocular Fusion

During each fixation, the two retinae receive slightly dissimilar visual inputs (i.e. disparate images). Regardless of this, however, we typically perceive a single, unified, high-resolution representation of the visual environment. In other words, the visual system continuously integrates the independent inputs received by each eye into a cyclopean (i.e., single, unified) percept. This integration process is termed binocular fusion (Skelton & Kertesz, 1991).

Compared with the monocular percept received by each eye alone, a fused binocular percept has certain advantages: it prevents diplopia (double vision) and provides a larger visual field, better visual acuity, and it plays a significant role in our ability to perceive depth (Cashell & Durran, 1989). The perception of depth based on binocular fusion of dissimilar retinal inputs is known as stereopsis, or stereoscopic vision, and has been the subject of thorough empirical investigation (Howard, 1995, 2012; Howard & Rogers, 1996, 2012; Read, 2015; Wilcox & Harris, 2010).

It is important to note that aside from binocular depth cues derived from interocular disparity, the visual system also makes use of an array of monocular depth cues, such as linear perspective, motion parallax, texture gradient, shading, etc. (see Howard, 2002 for review). Humans typically perceive depth by seamlessly combining many of these binocular and monocular cues. However, estimating depth from a single visual input using monocular cues alone is a challenging task which requires a significant amount of prior knowledge and understanding of the content and global structure of the environment being perceived (Saxena, Driemeyer, Kearns, & Ng, 2006). In contrast, stereo cues are based on the differences between two retinal inputs, and do not necessarily depend on the content of an image (e.g. random-dot stereograms, Bülthoff, Bülthoff, & Sinha, 1998; Julesz, 1971).

Binocular fusion and stereopsis result from a complex network of multiple neurovisual processes, involving oculomotor responses occurring simultaneously with shifts in gaze position (saccades) to cortical integration of separate visual inputs into a single percept (Partt-Johnson & Tillson, 2001; Rizzo, 1989; Schor & Tyler, 1981; Skelton & Kertesz, 1991). The different contributions of these components, as well as their anatomical and functional background, are described below.

1.3.1 Motor fusion and the vergence system

Motor fusion is driven by the disparity between the two retinal inputs: when monocular images are projected onto non-corresponding points of each retina, the eyes need to be adequately aligned in order to achieve and attain correspondence across eye movements (Rizzo, 1989). Thus, motor fusion comprises of the sophisticated oculomotor mechanisms by which the eyes change their position, so that corresponding points in each retinal image are superimposed. This is achieved through vergence movements: slow eye movements in opposite directions (disconjugate) that serve to adjust the angle between the two visual axes (Howard & Rogers, 1995; Schor & Ciuffreda, 1983) described how vergence movements are distinct from conjugate movements such as saccades: during vergence movements the two eyes rotate in opposite directions and either converge – move towards one another – or diverge – move away from one another (King & Zhou, 2000). On a physiological level, two antagonist extra-ocular muscles are involved in binocular horizontal vergence: the medial and the lateral rectus muscle. Contraction of the medial and simultaneous stretching of the lateral rectus muscles leads to the adduction of the eyeball, while, stretching of the medial and contraction of the lateral rectus muscles leads to abduction of the eyeball (Brodal, 2004).

But while horizontal vergence has been the primary subject of study by researchers interested in binocular vision, vertical vergence movements can also be executed. Such eye movements are typically made to correct vertical misalignment in the two visual inputs (Allison, Howard, & Fang, 2000; Busettini, Fitzgibbon, & Miles, 2001; Howard, Allison, & Zacher, 1997; Howard, Fang, Allison, & Zacher, 2000; Yang, Fitzgibbon, & Miles, 2003). They do, however, differ considerably from horizontal vergence movements. Indeed, early research investigating the characteristics of the vertical motor fusion revealed that when compared to its horizontal counterpart, it is limited in both amplitude and speed (Kertesz, 1981). For instance, Perlmutter and Kertesz (1978) reported that the maximum binocular image disparity that can be fused successfully is approximately five times smaller in the vertical than in the horizontal direction (see also Bharadvaj et al., 2007 for replication). In addition, they found that in contrast with horizontal fusion, the monocular contribution to a vertical motor fusional response is asymmetric in its time course and magnitude. That is, the vertical vergence response of each eye did not correspond to the step change of disparity in the stimuli.

Steinman, Steinman and Garzia (2000) further postulated that humans have limited capacity for vertical vergence movements, due to the physiological make-up of the visual system. More recently, Brautaset and Jennings (2005) assessed the horizontal and vertical vergence system during prism adaptation in participants diagnosed with convergence insufficiency (the inability to maintain binocular function at near distances). They concluded that horizontal and vertical motor fusion mechanisms serve independent but complimentary purposes in attaining binocular vision. Specifically, vertical vergence serves to maintain global eye alignment and keep the two eyes fixated on the same point in space. Overall, the two vergence systems appear to interact in the process of maintaining a single, unified percept of the fixated object.

On a neurophysiological level, a complex system is involved in the control of motor fusion (Zee, Fitzgibbon, & Optican, 1992). It involves the oculomotor nuclei of the cranial nerves III and VI, the frontal eye fields and lateral prefrontal areas, the visual cortices, lateral and medial parietal regions as well as midbrain areas around the oculomotor nuclei and the cerebellum (Alkan, Biswal, & Alvarez, 2011; Van Horn, Waitzman, & Cullen, 2013; Kapoula, Yang, Coubard, Daunys, & Orssaud, 2005; Mays, 1984; Freeman & Ohzawa, 1990).

Most oculomotor neurons have been shown to control both conjugate (version) and disconjugate (vergence) eye movements (Mays & Porter, 1984; Sylvestre, Choi, & Cullen, 2003). However, the midbrain houses three types of neurons involved specifically in the control of vergence: those that discharge in relation to vergence angle are known as vergence tonic cells, those that discharge in relation to vergence velocity are known as vergence burst cells, and those that relate to both vergence angle and velocity are known as burst-tonic cells (Judge & Cumming, 1986; Zhang, Mays, & Gamlin, 1992). At the cortical level, neurons in the primary visual cortex (V1) are involved in responding to different inputs in each eye and signalling stimulus depth (Prince, Pointon, Cumming, & Parker, 2002; Trotter, Celebrini, & Durand, 2004). In addition, microstimulation of the frontal eye field (FEF) in the frontal lobe can induce vergence eye movements, as this area contains neurons that discharge for convergence and divergence eye movements made in response to displacement of a target in depth (Fukushima et al., 2002; Gamlin & Yoon, 2000). The cerebellum, on the other hand, is responsible for error-detection and accuracy of vergence eye movements, and cerebellar lesions have been shown to lead to dysfunctional binocular convergence in both primate and human studies (Sander et al., 2009; Nitta, Akao, Kurkin, & Fukushima, 2008).

Overall, the above studies provide an indication of the widely distributed nature of motor fusion control. The differential interactions between multiple regions involved in executing vergence eye movements rely on continuous feedback between sensory subsystems carrying information about the current visual perception and oculomotor subsystems which sustain or change the point of regard.

It is important to note that vergence eye movements are typically accompanied by two monocular processes that serve to sustain a clear, “sharp” percept of the fixated stimulus: (1) the constriction of the pupil, known as miosis, and (2) the dynamic refraction adjustment of the lens known as accommodation (Crone & Hardjowijoto, 1979; Ciuffreda, Rosenfield, & Chen, 1997; Richter, Lee, & Pardo, 2000). These processes can be studied independently, but under normal viewing conditions, pupil constriction, accommodative and fusional drives work in unison when gaze is shifted between targets lying both at different distances and in different directions (Leigh & Zee, 2006).

1.3.2 Sensory Fusion

While vergence eye movements maintain binocular foveal alignment, the merging of two separate visual inputs into a single, unified representation is thought to be a subsequent neurocomputational process. This process is termed sensory fusion and is among the most fundamental characteristics of the human visual system. As stated above, in order for two separate visual inputs to be fused, they must be projected onto corresponding retinal locations (Rizzo, 1989). The locus of all object points in space that are imaged onto corresponding retinal locations – that is, all points in space that yield single vision – is known as the horopter. This geometrical locus provides the optical basis for sensory fusion and for further stereoscopic and/or cognitive processing associated with the fixated stimulus (Poggio & Poggio, 1984). The concept of the horopter was first described in the eleventh century by scholar Ibn al-Haytham, known also as Alhazen. Building on work by Greek mathematician and astronomer Ptoemy, Alhazen discovered that objects lying on a horizontal line passing through the fixation point resulted in single vision, while objects lying at a distance from that line resulted in double vision. The term horopter itself was introduced by Franciscus Aguilonius in 1613 (as cited by Helmholtz, 1910).

Determining the horopter – the combination of points in space for which sensory fusion can occur – is a problem that has been approached both from a geometrical optics and from a physiological optics perspective. Early work by Gerhard Vieth and Johannes Müller (described in Helmholtz, 1910) defined the horopter as the larger arc of a circle that passes through the fixation point and the centre of the lenses of the two eyes (nodal points, Howarth, 2011). According to this geometric definition, all points on this arc should stimulate corresponding points in the two retinae and lead to single vision. This theoretical horopter is known as the Vieth-Müller circle (Howard & Rogers, 1995).

With the invention of the stereoscope by Charles Wheatstone (1838) came the ability to explore the limits of sensory fusion empirically, by considering the psychological criterion of single vision. Wheatstone (1838) observed that there were many points in space not falling on the theoretical horopter for which single vision occurred. Similar observations were made by Panum (1858), suggesting that the empirical horopter, as defined by the perceptual experience of single vision, deviates from the Vieth-Müller defined by geometrical optics. In principle, for every point of fixation, the horopter is a region in space containing stimuli that simulate corresponding retinal locations. Objects outside the horopter (e.g. in front or behind it) produce retinal inputs that are disparate, either horizontally, vertically, or both. However, within a limited range of disparities, such objects can still be perceived as fused (see *Figure 1*). This range, also known as the functional fusional range, has been termed Panum's area (Panum, 1858; see also Cumming & DeAngelis, 2001; Rizzo, 1989; Poggio & Poggio, 1984).

Within Panum's area, two types of disparities can be differentiated. Objects in front of the horopter (e.g. when the object is between the horopter and the observer's egocentric location) have a crossed disparity, as the visual axes intersect. Thus, in order for these objects to be fixated, a higher amount of convergence is needed. In contrast, objects that fall behind the horopter (e.g. when the horopter is between the object and the observer) have uncrossed disparities and require a higher amount of divergence in order to be foveated. Importantly, objects that fall outside of the limits of Panum’s area are experienced as double, or diplopic.

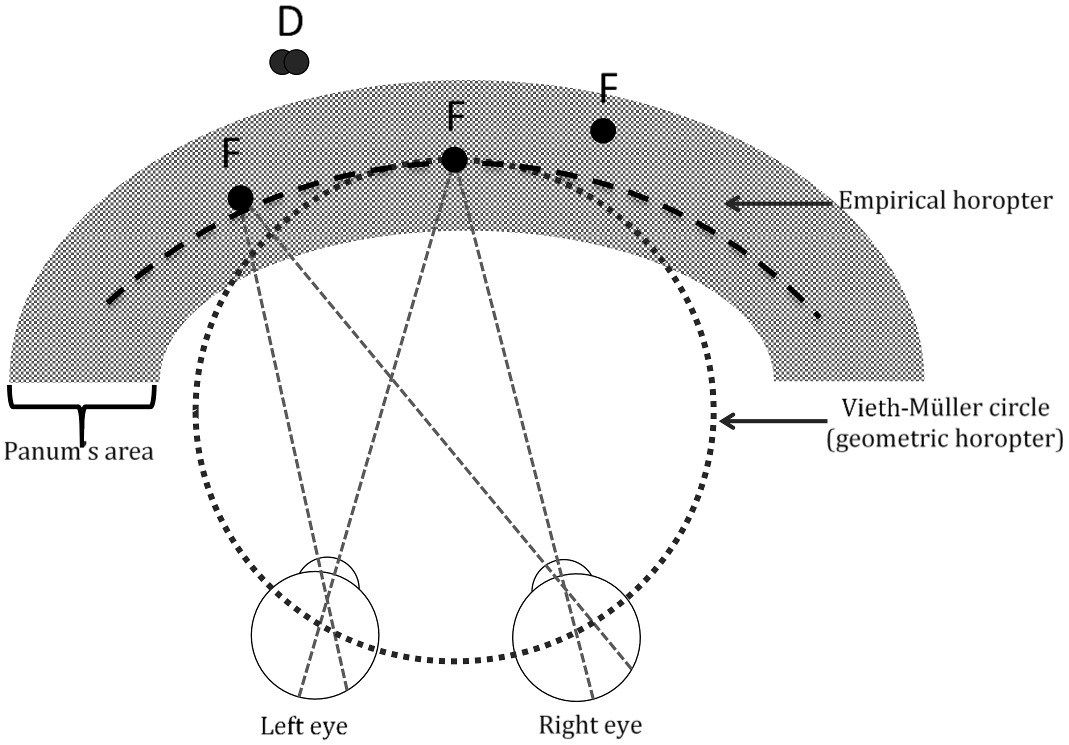


Figure 1. Representation of the Vieth-Muller circle (gometrical horopter), the empirical horopter, and Panum’s area. Points F (within Panum’s area) appear fused, whereas point D, which is outside of Panum’s area, appears diplopic.

Such large disparities can also trigger a motor fusion response, which serves to align the eyes in such a way that the two visual inputs fall within the limits of Panum’s area.

While the concept of the horopter is somewhat contentious, in that its definition depends on the criterion used to specify correspondence, researchers overwhelmingly agree that one important condition for achieving sensory fusion is visual similarity. For example, differences in stimulus size, shape, colour or brightness between the two eyes are an obstacle to successful sensory fusion (Von Noorden & Campos, 2003). Such differences produce an experience of binocular rivalry, in which conscious perception alternates between the images presented to each of the two eyes (Blake, 1989; Levelt, 1966; Tong, Meng & Blake, 2006).

It is important at this point to clarify that while a large number of studies have been conducted to explore sensory fusion of horizontal disparities, binocular disparity can also occur in other dimensions (e.g. vertical and cyclotorsional). Vertical disparities, for example, are particularly important when coding the distance to surfaces in depth, when judging the depth curvature of an object about a vertical axis, or the vertical slant of a surface (Backus et al., 1999; Duke & Howard, 2012; Ogle, 1938). Similarly to vertical motor fusion, however, vertical sensory fusion is less well-understood.

Read and Cumming (2006) explored the range of horizontal and vertical disparities in typical viewing situations. Based on their findings, they stipulated that because horizontal disparities are more common due to the position of the two eyes in the head, the visual system is likely to be more adept at processing them, implying that fewer resources would be devoted to vertical disparity processing. Indeed, this suggestion fits with psychophysical studies showing that even small amounts of vertical disparity can disrupt stereopsis (Farell, 2003; McKee, Levi, & Bowne, 1990). There is, however, ample evidence to suggest that vertical disparity can influence sensory fusion, primarily by altering the perception of depth caused by horizontal disparity (Backus, Banks, van Ee, & Crowell, 1999; Banks & Backus, 1998; Banks, Hooge, & Backus, 2001; Berends & Erkelens, 2001; Berends, van Ee, & Erkelens, 2002; Brenner, Smeets, & Landy, 2001; Clement, 1992; Duke & Howard, 2005; Friedman, Kaye, & Richards, 1978).

Importantly, with respect to sensory fusion, vertical disparities within the functional fusional range appear to be processed over a large area of the visual field, rather than locally, as is the case for horizontal disparities (Adams, Frisby, Buckley, Garding, Hippisley-Cox, & Porrill, 1996; Kaneko & Howard, 1995; Rogers & Bradshaw, 1995). Thus, the perceptual consequences of vertical disparity for sensory fusion may be explained by its effect on the reduction in binocular correlation between the visual inputs projected to each of the eyes, and consequently, the influence on horizontal disparity processing (see also Read & Cumming, 2006). In other words, similar to vertical motor fusion, vertical sensory fusion subserves the maintenance of a single, unified percept.

On a neurophysiological level, sensory fusion differs somewhat from the widely distributed cortico-subcortical nature of motor fusion. Sensory fusion relies on purely cortical neurovisual interactions, and is functionally highly similar in that regard to stereopsis (Westheimer, 2009). Visual inputs of either eye remain functionally and physically segregated until the primary visual cortex (V1), where the monocular input first converges (Rizzo, 1989; DeAngelis, 2000). Single cell recordings in monkeys have revealed highly specialized neurons in the primary and secondary (V2) visual cortex that fire for selective disparities on either side of the horopter (Poggio, Doty, & Talbot, 1977; Poggio & Talbot, 1981; Cumming & DeAngelis, 2001; Westheimer, 2009). Higher order visual processing areas of the parietal and temporal lobe are also involved in sensory fusion, but rather than encoding specific disparity signals, their function is believed to relate to providing a more refined analysis of disparity information (global stereopsis; Rizzo, 1989; Bruce, Green, & Georgeson, 2003; Poggio & Poggio, 1984; Ptito et al., 1992; Westheimer, 2009).

These findings indicate that sensory fusion is a hierarchical process, with disparity-selective neurons in multiple cortical areas. The hierarchical nature of sensory fusion is a concept put forth in early work by Worth (1921). He defined three grades of sensory fusion necessary for deriving the benefits of binocular vision. Firstly, unhindered simultaneous perception of each eye's image is required. During second-degree fusion the two retinal images are combined into a unified percept through the processes of binocular summation, binocular correspondence and fusion without depth. Finally, third-degree fusion with stereopsis, or binocular three-dimensional depth perception, is conceptualised as the highest degree of binocular visual function.

Binocular vision and stereopsis have long been known to aid the perception of size, distance and shape of objects. It fact, binocular vision has been shown to provide advantages in a variety of behavioural tasks. For example, Jones and Lee (1981) reported a series of ten experiments in which they compared binocular and monocular performance in a variety of tasks. They found binocular performance advantages for letter, colour and object discrimination, as well as for visuomotor tasks that involved object manipulation, reaching and balance. Similar findings were reported by Morris and O'Connor (2006), who found a performance deficit when tasks that required fine motor skills were executed monocularly, rather than binocularly. Grant and Moseley (2011) reviewed data from multiple studies comparing the performance of children and adults with amblyopia to that of control participants with normal binocular vision. They concluded that binocularity plays an important role in the ability to perform multiple real-world actions, regardless of whether the task has a depth of 3-dimensional component (e.g., driving) or not (e.g., drawing, reading). For the remained of this thesis, the focus will be specifically on the role of binocular vision for reading, a psychologically complex, important every-day cognitive task.

1.4 The role of binocular vision in reading

As the above sections have shown, binocular fusion, vergence eye movements and stereopsis have been the subject of extensive empirical investigation (Howard & Rogers, 2012; Scheiman & Wick, 2008; Steiman et al., 2000). In addition, as demonstrated by the first part of the introduction, a vast, detailed literature has explored various characteristics of eye movements during reading, such as fixation durations, saccade amplitude, the amount of text required for smooth uninterrupted processing (perceptual span), as well as visual and cognitive mechanisms affecting the decision of when and where to move the eyes (see Rayner, 1998, 2009 for review).

However, coherent systematic research of binocular coordination and the role of binocular vision during word recognition and written language processing is surprisingly scarce in comparison (Kirkby, Webster, Blythe, & Liversedge, 2008).

A plausible explanation for why reading has received little attention by researchers interested in binocular vision is the assumption that because written text is usually 2-dimensional, processing it does not typically require stereopsis, or large eye-movements in depth (Van Leuween et al., 1999). This is also a likely reason why the vast majority of researchers interested in eye movement control during reading have reported data from monocular eye tracking experiments (see also Liversedge, 2008). In recent years, however, researchers interested in reading have begun to consider the role of binocular vision and binocular coordination in this complex psychological process. The following sections reviews some of the key findings in this area.

1.4.1 Binocular coordination and vergence eye movements in reading

The growing literature on binocular coordination during reading has distinguished several key lines of study: the presence and basic characteristics of fixation disparity in reading fixations, the involvement of the motor and sensory fusion system in reading, the influence of processes related with binocularity on word identification and the programming and targeting of binocular eye movements.

Some of the earliest observations of fixation disparity in reading were made by Hendriks (1996). She was interested in the nature of vergence movements made during fixations while reading sentences or lists of single words with varying difficulty. She reported a tendency for the eyes to converge during the majority of fixations. In addition, she observed that vergence velocities were higher when reading text passages as opposed to single words, and when participants read for comprehension, rather than for subvocal pronunciation. Those findings were interpreted as an indication that binocular coordination during reading can differ as a function of task: under conditions where contextual information was unavailable (reading lists of words), saccades were smaller in amplitude and fixation stability was higher, compared to conditions where context or comprehension were involved.

Radach, Heller, Weibories, and Jaschinski (1996) and Heller and Radach (1999) reported similar findings to Hendriks (1996) with respect to the coordination of the eyes during fixations in reading. They provided further accounts of asymmetrical saccades during reading, such that the abducting eye (moving temporally) made a larger, faster movement than the adducting eye (moving nasally) on 70%-90% of saccades. This often resulted in the two eyes landing apart, possibly on different characters within a word, and convergent movements being made during the fixations.

Those results were in accord with earlier observations in non-reading tasks by Collewjin, Erkelens and Steiman (1988), who examined binocular coordination in participants making saccades between several light-emitting diodes (LEDs). The typical oculomotor pattern for adults without visual problems was as follows: during the initial part of a saccade, the abducting eye (moving temporally) typically makes a larger, faster movement than the adducting eye (moving nasally). This systematic difference in velocity results in transient divergence throughout the saccade, which results in a fixation disparity on fixation onset. The eyes then tend to converge during fixations in order to reduce fixation disparity and attain a stable percept of the fixated stimulus.

More recent studies used sophisticated binocular eye tracking methodology to investigate this pattern of saccadic disconjugacy and fixation disparity, and to estimate the proportion of fixations during normal reading in which the two eyes do not land on the same character within a word. For example, Liversedge, White, Findlay and Rayner (2006a) explored the magnitude and direction of fixation disparity during reading, the nature of resulting vergence movements and the influences of eye dominance. Their results indicated that the two eyes were aligned (i.e. fixating on the same character within a word) in approximately 53% of fixations. The rest of the time the two fixation points were misaligned: either the left eye lands further to the left in relation to the right eye (termed uncrossed or exo-fixation disparity, 39% of cases) or the left eye lands further to the right than the right eye (crossed or eso-fixation disparity, 8% of cases). The average magnitude of disparity during misaligned fixations was approximately 1.9 character spaces. Systematic vergence movements occurred during fixations to reduce the misalignment; however, at the end of fixations at least 1 character space of disparity was still present approximately half the time.

While Liversedge at al. (2006a) only considered fixation disparity at the beginning and at the end of each fixation, Vernet and Kapoula (2009) complemented the growing literature on binocular coordination in reading by investigating disparity over multiple time periods during a saccade and the first 160ms of a fixation. They largely replicated the findings reported by other research groups, as well as the pattern of oculomotor behaviour reported by Collewjin et al. (1988). Vernet and Kapoula (2009) found that the eyes tended to diverge during saccades in reading, resulting in saccade disconjugacy that carried over to the beginning of fixations.

Following repeated findings of fixation disparities and vergence adjustments during reading, researchers began to consider how different orthographic, linguistic and visual factors might affect binocular coordination during reading. For example, Juhasz, Liversedge, White and Rayner (2006) investigated the effect of orthographic complexity on fixation disparities in reading by presenting sentences in a mixed case font (e.g. *MiXeD CaSe*). In addition, they explored the influence of lexical characteristics on binocular coordination by including a frequency manipulation. As mentioned previously, the frequency effect is a well-established finding in reading research: high-frequency words, which occur commonly in the language, are typically processed faster than low-frequency words, which tend to be more difficult to process and occur less often (Inhoff & Rayner, 1986; Rayner, 1998; White, 2008). Juhasz et al. (2006) speculated that perhaps the higher cognitive load associated with the processing of more difficult words might affect the tolerance of the visual system for fixation disparities. The authors found that binocular misalignment was present in 45% of fixations, with predominantly uncrossed disparities. They did not, however, find an effect of either the frequency or the case manipulation on binocular coordination. In other words, the presence of fixation disparity was a robust finding regardless of orthographic complexity and cognitive processing difficulty.

The stability of binocular coordination processes under different text presentation conditions during reading was also investigated by Jainta, Dehnert, Heinrich and Jaschinski (2009). They explored eye movements during reading of blurred and unblurred text. Their findings indicated that while saccadic disconjugacy was not affected by blur, fixation disparity was: the eyes diverged more when reading blurred, compared to non-blurred text. The authors reported that the observed exo-shift in vergence during fixations correlated with individual differences in accommodation and heterophoria (the resting state of the eyes when no binocular fusion stimulus is present). They concluded that binocular coordination during reading is generally robust in conditions with moderate levels of stimulus degradation, but is influenced by individual optical profiles and processes associated with the coupling of vergence and accommodation (see also Hung, 2011; Jainta, Hoormann, & Jaschinski, 2009; Schor, 1999).

Another important source of influence on binocular coordination processes during reading in individuals with normal vision is age. For instance, Blythe, Liversedge, Joseph, White, Findlay and Rayner (2006) observed the same pattern of fixation disparity with both adults and children. They did, however, report that children were found to make on average a larger proportion of crossed fixations than adults, with a larger magnitude of disparity. In other words, children's binocular coordination was less precise than that of adults. These findings, as well as others (see Bucci & Kapula, 2006; Bucci & Seassau, 2012; Lions, Bui-Quoc, Seassau, & Bucci, 2013) reflect the maturation of both reading skill and eye movement control with age, and are supported by evidence that cortical structures associated with oculomotor and linguistic processing undergo development during childhood and adolescence (Turkeltaub, Gareau; Flowers, Zeffiro, & Eden, 2003; Luna, Thulborn & Munoz, 2001).

Overall, research into binocular coordination has disputed the assumption of perfect binocular fixation alignment during reading. Studies have now shown that while motor fusion (i.e. vergence movements) is present during reading fixations, fixation disparities do not typically disrupt language processing. Furthermore, binocular coordination mechanisms appear to be largely consistent across different manipulations of the visual quality or orthographic complexity of the text and are not influenced by cognitive load.

Interestingly, while the presence of fixation disparities in reading is now an undisputed finding, some uncertainly remains about the prevalence of exo- over eso- disparities. A number of studies have reported that the majority of fixation disparities observed in skilled adult readers tend to be crossed, or eso (Kliegl et al., 2006; Nuthmann & Kliegl, 2009; White, Staub, Drieghe & Liversedge, 2011). This is in contrast with many of the above-mentioned studies, which generally report a tendency for the eyes to diverge during saccades, thus resulting in a majority of uncrossed fixation disparities. The exact reason for this difference in the direction of disparities is not yet entirely clear, but several potential explanations have been empirically tested. For example, Kirkby, Blythe, Drieghe, Benson and Liversedge (2013) noted that reading experiments which reported predominantly uncrossed disparities were usually conducted using Dual-Purkinje Image (DPI) eye-trackers, and text was presented in a light font over a dark background. In contrast, experiments reporting predominantly crossed disparities typically utilised SR Research EyeLink eye-trackers, and the viewing conditions were different (i.e. dark text over light background). Therefore, Kirkby et al. (2013) speculated that perhaps specific characteristics of the eye tracking acquisition hardware and analyses software might explain the difference in the reported findings regarding fixation disparity. They conducted a reading experiment to test that hypothesis by directly comparing eye movement data from both eye-tracking systems, using the same participants and the same stimuli. Viewing conditions were typical for DPI experiments: light text was presented over dark background. The results indicated that while disparity magnitude, as measured with the EyeLink system, was generally larger than that obtained from the DPI system, the majority of binocular disparities were uncrossed regardless of eye-tracking acquisition and analyses software.

Kirkby et al. (2013) concluded that factors other than the particular eye-tracking equipment used could contribute to the differences in predominant direction of disparity observed in the previous literature. One of those factors might be the specific viewing conditions of each experiment (e.g. luminescence, font size, viewing distance etc.), as also indicated by

Nuthmann, Beveridge and Shillcock (2014). In addition, Jainta and Jaschinski (2012) postulated that every individual's heterophoria may be correlated with aspects of their fixation disparities. Heterophoria describes a latent deviation or misalignment of the visual axes that is apparent when binocular fusion is prevented, usually by presenting a single target to one eye only. It reflects tonic vergence (i.e. resting vergence state in the absence of disparity) and is often asymptomatic (Carter, 1965; Fry, 1964). Jainta and Jaschinski (2012) found on average more eso-disparities in participants with esophoria (a tendency for the eyes to converge) and more exo-disparities in participants with exophoria (a tendency for the eyes to diverge). Therefore, it is likely that individual differences in certain characteristics of the oculomotor system may contribute to the different direction of fixation disparities reported in different studies.

Regardless of the reported differences, all of the studies cited above demonstrate the crucial role of eye movements for maintaining a non-diplopic perceptual representation in reading: through a rapid sequence of fixations and saccades interlaced with vergence movements, the visual system controls the magnitude of retinal disparity from one fixation to the next, ensuring that no diplopia is experienced while processing text. Crucially, this single, unified percept is the foundation for the cognitive and linguistic processes that take place during natural sentence reading.

Once it was established without doubt that the vergence system is involved in reading, a second line of research into binocularity began to focus on specific questions regarding binocular fusion, its limits and its interplay with the various processes involved in written language processing. For example, Liversedge, Rayner, White, Findlay, and McSorley (2006b) addressed the question of how saccades are programmed during sentence reading on the basis of disparate retinal inputs. Their experiment involved reading sentences which had a dichoptically presented target word within them (i.e. the visual input received by each eye was individually manipulated when participants fixated on the target word). A target compound word (e.g. cowboy) was presented in 3 conditions: a) both eyes saw the entire word; b) the left eye was presented with *cowb* and the right eye was presented with *wboy* (congruent); c) the left eye was presented with *wboy* and the right eye was presented with *cowb* (incongruent). The analysis revealed that landing positions on the target word were unaffected by the dichoptic presentation manipulation and the proportion of crossed, uncrossed and aligned fixations was almost identical across presentation conditions. It was concluded that despite reception of separate retinal inputs, the visual system programmed saccades on the basis of a single unified representation of the stimulus, likely achieved at an early stage of processing via a process of fusion, rather than suppression or rivalry.

Those findings sparked further research into the process of sensory fusion in reading, its time course and its limits. For instance, Blythe, Liversedge and Findlay (2010) conducted a study to examine the magnitude of Panum's area for linguistic stimuli. Their experiment aimed at actively driving a vergence response from the visual system. Their research also addressed limitations in the previous literature regarding the magnitude of Panum's area. Blythe and colleagues employed eye-tracking methodology to attain an accurate index of retinal disparity, which had not been achieved in previous studies. Additionally, they studied different aspects of eye movement behaviour in response to binocular image disparity: vergence movements in relation to saccadic targeting, saccade landing positions, the time course of fusion and vergence movements during fixations. Blythe et al. presented stimuli dichoptically, as per Liversedge et al. (2006b). Single words were presented to both eyes in 5 stereoscopic conditions, where the two dichoptic images were either aligned, or offset horizontally by 1 or 2 character spaces of crossed or uncrossed disparity. Participants were required to indicate via a button press if they saw a word or a non-word. Findings indicated that the functional fusional range for linguistic stimuli extended to approximately 1 character space of crossed or uncrossed disparity, corresponding to 0.37^{o} of visual angle. Disparities beyond that range elicited appropriate vergence movements, attempting to bring the offset images within Panum's area. Importantly, this measured magnitude of Panum's area was identical in adults and children, suggesting that despite children's tendency to display larger fixation disparities than adults, their ability to fuse them is not superior.

While Blythe and colleagues contributed significantly to the growing understanding of fusional processes in reading, it is important to note that fixation disparity generally occurs in three directions: horizontal, vertical and torsional (associated with head tilt along a nasal-occipital axis). Thus, the fusional mechanisms involved in maintaining stable binocular vision are characterised by horizontal, vertical and cyclotorsional fusional responses (Boman & Kertesz, 1981). While there is now a considerable body of work investigating characteristics of horizontal motor fusion and horizontal convergence in reading, few studies so far have systematically investigated misalignments in reading in other dimensions. As mentioned earlier, vision scientists have shown that vertical disparities can be encountered in a number of natural viewing conditions (Read & Cumming, 2004) and may thus play an important part in the ability to maintain a stable, unified percept of written text.

In terms of reading research, recent work by Nuthmann and Kliegl (2009) did report the presence of vertical misalignments in each reading fixation of about a similar magnitude to horizontal disparities. Nevertheless, their findings regarding vertical disparity were purely descriptive and no claims were made about any potential vertical vergence adjustments during fixations. In addition, Jainta, Blythe, Nikolova, Jones and Liversedge (2015) conducted a detailed investigation of disparities occurring during natural sentence reading. They reported that vertical disparities were of much smaller magnitude than horizontal disparities, and observed no significant change in vertical vergence during reading fixations. Jainta and colleagues suggested that the limited activation of the vertical vergence system during reading could be due to functional differences between horizontal and vertical disparities and disparity reducing mechanisms in relation to maintaining a single unified perception of the written text. Namely – similar to non-reading studies – while horizontal vergence movements in response to horizontal disparities are central for depth perception and stereopsis, vertical vergence movements are likely to have a sub-servient role in maintaining the global alignment between the two retinal inputs and ensuring a stable percept over which horizontal fusional processes can operate.

In summary, the studies reviewed above demonstrate clearly that (1) binocular coordination processes are involved in saccades and fixations during reading and (2) binocular fusion serves to maintain a single, unified perceptual representation of the text across eye movements. When the visual system encounters horizontal disparity during reading, vergence movements occur to reduce it and to help maintain a unified percept of the text. This cyclopean (i.e. single) percept is the foundation upon which all subsequent cognitive and linguistic processing is based.

1.4.2 The advantages of binocular vision for reading

Existing studies have repeatedly demonstrated that while fixation disparities are typically observed in reading, they do not cause disturbances to lexical processing. That is, readers with normal binocular vision are able to easily resolve these disparities and maintain a stable, unified percept of the text across fixations and saccades. Importantly, for individuals with normal vision, binocular coordination remains fairly robust and is not strongly affected by orthographic complexity, cognitive load or moderate visual degradations (Jainta et al., 2009; Juhasz et al., 2006).

What is less clear, however, is the degree to which binocular vision contributes to reading performance. For example, several studies have shown faster reading rates for binocularly presented, relative to monocularly presented sentences (Heller & Radach, 1998; Jainta et al., 2014; Jainta & Jaschinski, 2012; Sheedy, Bailey, Buri, & Bass, 1986). Nevertheless, as shown earlier in this chapter, multiple factors determine the speed with which words are processed during sentence reading. It is important, therefore, to consider the mechanisms via which the presence of binocular visual input exerts its influence on sentence processing times.

The first study to consider this question was conducted by Jainta, Blythe and Liversedge (2014). They employed novel application of the boundary paradigm (Rayner, 1975). Recall that in this paradigm, an invisible boundary is placed in the space before a target word. Prior to the reader crossing that boundary, the target word may be presented correctly, or manipulated in various ways. However, as the reader's eyes cross the boundary, a rapid display change occurs and the word is presented correctly upon fixation.

In their version of this experimental technique, Jainta et al. (2014) placed an invisible boundary before a designated target word manipulated for lexical frequency, and presented text either binocularly or monocularly prior to the reader's eyes crossing the boundary. Once the boundary was crossed, the mode of presentation for the rest of the sentence either remained unchanged, or was switched. This resulted in four reading conditions for the target word and its parafoveal preview prior to direct fixation: 1) the target could be previewed binocularly, but fixated monocularly, 2) it could be previewed monocularly but fixated binocularly, 3) both preview and fixation could be binocular and 4) both preview and fixation could be monocular. This manipulation enabled the authors to directly observe the effect of changing the quality of the binocular input during foveal and parafoveal processing by comparing the size of the word frequency effect across all presentation conditions. They reported that when reading was monocular, the robust frequency effect which was observed in binocular reading was considerably diminished. That is, when the target word was both previewed and fixated monocularly, participants were not able to process it more efficiently if it was a high-frequency word than if it was a low-frequency word. Furthermore, when foveal presentation was monocular, a frequency effect was observed only if the parafoveal preview of the word was binocular. In other words, there was a clear benefit to lexical processing when parafoveal information was available binocularly. Correspondingly, when the parafoveal preview was monocular, a frequency effect was only obtained for binocular and not monocular target word presentation upon direct fixation.

These findings clearly demonstrate a binocular advantage for both foveal and parafoveal processing during reading. In addition, they show that the superior reading performance observed during binocular reading is not limited to measures of global eye movement behaviour, but can also be seen in local measures of word identification. This hints at the complex interplay that exists between visual processing and cognitive processing, which is fundamental for humans' ability to efficiently process written text.

Critically, further work by Jainta, Nikolova and Liversedge (2017) provided evidence that the binocular advantages reported by Jainta et al. (2014) could not be attributed to entirely differences in the visual characteristics of text between binocular and monocular viewing conditions. Specifically, Jainta and colleagues (2016) considered the potential influence of visual contrast on binocular advantages. They presented sentences in four experimental conditions: 1) binocularly, 2) monocularly, 3) binocularly with contrast reduced to resemble monocular conditions and 4) binocularly with a large contrast reduction, exceeding that occurring when naturally switching from binocular to monocular presentations. Their findings revealed an interesting pattern of results. Firstly, when comparing binocular and monocular reading, they replicated the binocular advantage for word identification observed by Jainta et al. (2014). That is, they found that in monocular conditions, high-frequency words were identified at the same speed as low-frequency words. However, this pattern was not observed in the conditions where contrast was reduced. In fact, with both levels of contrast reduction, there was a robust frequency effect, and reading was slowed down overall when the reduction was large enough to approximate the detection threshold.

It is important to note that these findings do not entirely rule out the possibility of visual quality influencing binocular advantages in reading. The contrast reduction manipulation employed by Jainta et al. (2017) was based on the binocular summation ratio, or the ratio of binocular to monocular sensitivities. This ratio is approximately 1.4 (√2) and has been measured primarily for sine-wave gratings (Blake & Fox, 1973; Blake, Sloane, & Fox, 1981; Campbell & Green, 1965). In other words, early work has shown that binocular contrast sensitivity for sine-wave gratings is about 1.4 times as high as monocular contrast sensitivity, which led Jainta and colleagues to theorise that a contrast reduction of binocular text to 70% (about 1.4 times lower than full contrast) would resemble the reduction in contrast that occurs when switching from binocular to monocular presentation. However, the binocular summation ratio has not been measured specifically for written text, which can have a spatial frequency profile different from that of sine-wave gratings. In fact, Bacon (1976) and Blake and Levinson (1977) found that binocular sensitivity varied as a function of the degree to which the spatial frequencies received by the two eyes differed (highest sensitivity was recorded for identical spatial frequencies). A further point is that the processing of written text involves both bottom-up encoding of visual information and top-down processing influences (McClelland & Rumelhart, 1981). In fact, these top-down influences have served as an explanation for the word superiority effect, whereby letters are reported more accurately when they are presented within a word than when they are presented within a non-word or in isolation (Johnston, 1981). The full extent to which word superiority influences reading performance and lexical identification under monocular presentation conditions and under conditions of reduced contrast is yet to be understood.

Nevertheless, the contrast manipulation and the monocular presentation employed by Jainta and colleagues produced distinctly different patterns of results with respect to the lexical frequency manipulation. Those findings led Jainta et al. (2017) to conclude that binocular advantages in reading cannot be entirely attributed to differences in stimulus quality between monocular and binocular presentation conditions. In other words, the authors postulated that perhaps in monocular reading conditions, there is a critical change in the capacity with which the psychological systems that process visual information after it has been encoded can operate. In the case of reading, the function of the linguistic processing system, and specifically, the lexical processor, might be dramatically reduced. Thus, the reduced efficiency in the lexical identification of high frequency words that occurred under monocular viewing conditions arose as a direct result of a global reduction in activation within the lexical identification system. Critically, both the above studies (Jainta et al., 2014, 2017) demonstrated that the availability of binocular visual input during reading not only improves global reading performance, but also has a clear influence on factors that affect the decision of when – and, potentially, where – to move the eyes.

1.4.3 Binocularity in the broader context of word recognition and reading

The question of how binocular coordination and binocular fusion may fit within a broader theoretical framework of word identification and reading has not been the subject of systematic empirical investigation. Nevertheless, some suggestions can be made on the basis of existing computational models of word recognition, such as the Interactive Activation (IA) model (McClelland & Rumelhart, 1981). The central feature of the AI model is that of a multilevel processing system for linguistic stimuli: the assumption is that there are separate levels of representation for visual features, letters and words. Furthermore, the IA model assumes that processing is interactive, meaning that it involves both bottom-up input of information and top-down knowledge-based constraints. It may be the case that within this context, binocular vision plays a part both as a bottom-up and a top-down influence on word identification. For example, binocular fusion (i.e. obtaining a single percept of the text) may be a necessary prerequisite for identifying features and letters and accessing the mental representation of a word. Alternatively, a binocular percept of the word may provide an advantage with relation to accessing top-down knowledge about a word's lexical frequency more efficiently and using that knowledge to aid lexical identification (as suggested by Jainta et al., 2014, 2017).

It is important to bear in mind that during normal reading, word recognition takes place within a dynamic context that involves rapid, precisely coordinated eye movements and successful integration of multiple words within a sentence-level representation. This means that binocularity may be implicated both in word recognition itself and in eye-movement guidance processes associated with deciding where to move the eyes (i.e., selecting saccade targets). Consider, for instance, the *ideal-observer* model of reading known as Mr. Chips (Legge, Klitz, & Tjan, 1997; Klitz, Legge, & Tjan, 2000). Mr. Chips was designed to optimally integrate visual, lexical and oculomotor cues in a way that would enable it to read simple text in a minimum number of saccades. Three key sources of information are used by Mr. Chips to achieve maximum reading efficiency: the visual span (the number of letters that can be identified in a single fixation), a lexicon consisting of all possible words and their probabilities of being identified based on the available visual information, and statistical knowledge of eye movement accuracy (i.e. knowledge of the probability distribution of landing positions). With these sources of information, Mr. Chips performs well at "reading" by making a saccade that minimises the uncertainty about the identity of the saccade target, and then leaving that target when the uncertainty has reached zero (i.e. the word has been identified). There are at least three possible ways in which binocularity could exert influence over eye movements in the context of Mr. Chips. First, binocular vision might allow for the maximum number of letters to be identified during a single fixation, thus providing a wider visual span. Second, the availability of binocular visual input might affect the amount of visual information that is necessary to identify a word, thus increasing the probability of faster word identification. Finally, binocular input might be necessary in order to accurately target saccades, meaning that it would influence the probability distribution of landing positions.

While it is possible to incorporate binocular vision into the ideal-observer model of eye movement control in reading, it is important to point out that Mr. Chips was not designed to accurately represent natural reading. In fact, its purpose was not to comprehend meaning from text, but to "read" a series of unrelated words. In contrast, models of eye movement control in reading such as SWIFT (Engbert, Longtin, & Kliegl, 2002) and E-Z Reader (Reichle, 2011; Reichle, Rayner, & Pollatsek, 2003) attempt to computationally represent eye movement behaviour in a typical reading situation in which words are not only identified individually, but also incorporated into a sentence-level semantic representation. Both SWIFT and E-Z Reader assume that word identification is the primary drive for moving the eyes forward in the text. The central difference between them lies in their interpretation of how attention is shifted from one word to another. According to SWIFT (Saccade-generation With Inhibition from Foveal Targets), attention is distributed across several words in an attentional gradient. The words are processed in parallel until one of them reaches a level of activation at which lexical identification can be considered imminent. This word then becomes the saccade target, an eye movement towards it is executed and the attentional gradient changes to include other as yet unidentified words.

In contrast, E-Z Reader assumes that attention in shifted in a serial, sequential fashion from one word to the next. This assumption is based on the importance of word order for acquiring meaning from text in English. Once the fixated word (word N) reaches a level of activation where lexical identification is imminent, attention is shifted to the following word (word N+1) and a saccade programme is initiated. If word N+1 is recognised during the labile stage of saccade programming (i.e., because it is a very short, easy word or is highly predictable from the sentence context), it is possible for the saccade programme to be cancelled and for a new saccade to be initiated to word N+2.

Despite their different assumption about the distribution of attention during reading, both SWIFT and E-Z Reader agree, similarly to Mr. Chips, that eye movement guidance in reading is influenced by visual, cognitive and oculomotor factors. Furthermore, both E-Z Reader and SWIFT take into account the fact that during reading, information is processed not only from the currently fixated word, but also from words in the parafovea that are yet to be fixated (Rayner, 1998; Schotter et al., 2012). Thus, with relation to both models, binocular vision could potentially facilitate the processing of foveal information or enhance the pre-processing of parafoveal information, or both. In this way, binocularity might affect visual, oculomotor and cognitive processes that take place during reading and influence the decision of where and when to move the eyes. Potential mechanisms of such influences are discussed in detail in the following empirical chapters.

1.5 Synthesis and Direction for the Present Thesis

Various characteristics of eye movement behaviour in reading have been examined empirically over the past 50 years. In addition, a wealth of research has investigated characteristics of binocular fusion processes with relation to depth perception and stereopsis (Howard & Rogers, 2012; Steinman et al., 2000). In comparison with these vast areas of research, the investigation of binocular visual processes during reading is relatively recent (Kirkby et al., 2008). Nevertheless, the existing studies have shown that binocular fusion processes play an important part with relation to successful reading. Precise binocular coordination is required to maintain a single, unified representation of the written text across eye movements and to successfully encode words within sentences. Researchers have also demonstrated that the absence of binocular visual input influences not only the oculomotor processes associated with binocular fusion (i.e. vergence movements), but also the very fundamental ability to identify words efficiently.

Critically, however, the absence of common focus between the two groups of scientists – those interested in binocular vision with relation to stereopsis and those using eye movement methodology to study cognitive processes during reading – means that, despite recent progress in this field, the mechanisms via which binocular fusion informs oculomotor control and text comprehension during reading have remained largely underspecified. This means that our understanding of the relationship between this core characteristic of human visual function and the cognitive bases of how individuals represent and process written language is fundamentally limited. This significant limitation in our present understanding provides the theoretical context for the three experimental studies presented in this thesis.

Two core issues are the key subject of interest in the present thesis. Firstly, the present understanding of how motor and sensory fusion operate during word identification is incomplete. Only one study so far (Blythe et al., 2010) has considered the size of Panum's area for linguistic stimuli. This is critical, because a number of studies have demonstrated that the limits of Panum's area differ considerably for different stimuli (Fender & Julesz, 1967; Schor & Tyler, 1981; Qin et al., 2006). In fact, the perception of stereopsis has been shown to demonstrate properties of hysteresis – a phenomenon in which the value of a physical property lags behind changes in the effect causing it. For example, Fender and Julesz (1967) found that once the visual system achieves fusion, the perception of stereopsis is maintained, even if disparity increases. That is, if two disparate images are presented separately to each of the eyes and brought together, the maximum disparity permitting fusion is only approximately 7 minutes of arc. In contrast, if the two separate images are pulled apart after fusion has been achieved, the tolerance for disparity before stereopsis is disrupted increases to about 2 degrees of visual angle.

This property of binocular fusion has been studied primarily with random-dot stereograms or nonius lines. Written text, however, consists of visual stimuli that differ considerably in shape, complexity and spatial frequency profile from the stimuli typically used in non-reading studies. Furthermore, it is not clear whether – and to what extent – the additional processing demands associated with encoding and recognising a word may influence the limits of fusion during reading. In addition, no studies up to this point have considered the functional fusional range for vertical disparities during reading, resulting in an incomplete representation of the fusion process as a basis for word identification. Both these issues are addressed in Chapter 2.

A second question relevant to the present thesis concerns the nature of the binocular advantages observed during reading (Jainta et al. 2014, 2017; Jainta & Jaschinski, 2012). While the authors postulated that improved binocular performance in reading is likely associated with an increased capacity for lexical processing during binocular presentation conditions, the mechanisms of this effect are still not entirely clear. For example, it may be the case that binocular vision facilitates either foveal, or parafoveal processing, or both simultaneously. The goal of the experiment presented in Chapter 3 is to determine which of the mechanisms associated with word identification was influenced by binocular vision. Chapter 4 further extends those findings by considering the amount of binocular visual input needed in the parafovea and its influence on saccadic targeting and pre-processing of upcoming text.

The following chapters present a series of experiments and begin by considering binocular fusion in the context of single-word identification. Afterwards, the experiments explore binocular advantages in natural sentence reading, where binocular fusion takes place alongside oculomotor, linguistic and semantic processes, all of which interact in the seemingly effortless task of comprehending text. All the issues outlined above are of particular importance when attempting to develop a detailed, comprehensive understanding of binocular vision and its role in reading.

Chapter 2: Vertical Fixation Disparity during Lexical Identification

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2.1 Introduction

Humans sample their visual environment by continuously orienting their eyes towards objects of interest in a sequence of saccades and fixations. Saccades are rapid ballistic movements of the eyes in the same direction that serve to redirect the visual axes to a new location. They are interspersed with brief periods of relative stillness, known as fixations, during which visual information is encoded (see Rayner, 1998 for review). Even though we sample visual information with two frontally placed and horizontally separated eyes, we perceive a single unified representation of the visual environment. This single percept is achieved via the sophisticated mechanisms of binocular fusion, which have been made functionally possible by the development of a vergence system that allows us to coherently merge the visual input received by each eye (Howard & Rogers, 1995; Schor & Ciuffreda, 1983).

Binocular coordination is required for efficiently performing a variety of tasks, including reading, which does not call for stereopsis, or large eye movements in depth (van Leeuwen et al., 1999). Since humans typically make use of both eyes during reading, it is important to understand how binocular coordination might impact on contributing processes involved in written language comprehension. It is relatively recently that research has begun to focus on the detailed investigation of binocular coordination during reading. A number of studies have revealed that during text processing, the two visual axes are often slightly misaligned, resulting in small vergence errors (i.e. fixation disparities) of more than 1 character space in a significant proportion of fixations (Blythe, Liversedge, & Findlay, 2010; Blythe et al., 2006; Juhasz et al., 2006; Liversedge et al., 2006a; Liversedge et al., 2006b; Nuthmann & Kliegl, 2009; Vernet & Kapula, 2009).

It has been established that because the stimulus in reading necessitates predominantly horizontal yoked eye movements, some transient divergence occurs during saccades, followed by horizontal misalignment on fixation onset (Collewijn et al. 1988; Hendricks, 1996; Yang & Kapoula 2003; Zee, Fitzgibbon, & Optican, 1993). Fine-grained oculomotor adjustments are then made during fixations in order to maximize the degree of correspondence between the two disparate retinal input (Jainta et al., 2010; Jainta & Jaschinski, 2012; Leigh & Zee, 2006). Thus, during reading, the visual system is primarily faced with horizontal disparities, which might be the reason why research in written language processing has focused mainly on horizontal binocular coordination (Blythe et al., 2010, Liversedge et al., 2009, see Kirkby et al., 2008 for review). Indeed, few studies so far have systematically investigated misalignments in reading in other dimensions, a limitation to the comprehensive understanding of binocular coordination that the current work aimed to address.

Generally, in every task high-precision binocular vision is attained via the process of fusion, which incorporates two integral components: motor and sensory fusion (Partt-Johnson & Tillson, 2001; Schor & Tyler, 1981). Sensory fusion is a neurophysiological and psychological process whereby two independent representations are combined in the visual cortex into a single unified percept as a basic step for further processing (Howard & Rogers, 1995; Worth, 1921). Sensory fusion is only possible within a limited range of retinal disparities known as Panum’s fusional area (Schor, Heckmann, & Tyler, 1989; Steinman, Steinman, & Garzia, 2000). Larger disparities typically trigger a motor fusional response, or cause diplopia. Motor fusion comprises of the aforementioned physiological mechanisms of vergence, that is, slow disconjugate eye movements that serve to adjust the angle between the two visual axes and are mainly triggered by retinal disparity (Schor, 1979).

When conceptualizing the visual system’s response to binocular misalignment, it is important to note that disparities occur in three directions: horizontal, vertical and torsial. Thus, binocular motor fusion is characterised by horizontal vergence (along a plane containing the interocular axis), vertical vergence (along a plane orthogonal to the interocular axis) and cyclovergence (in opposite directions along the two visual axes, Boman & Kertesz, 1981; Howard & Rogers, 2012). While a significant body of work has investigated vergence movements driven by horizontal misalignments, the literature concerning responses to vertical and torsial disparities is considerably limited, particularly in the context of lexical processing. Though recent work by Nuthmann and Kliegl (2009) did report the presence of vertical misalignments in each reading fixation, their findings regarding vertical disparity were purely descriptive and no claims were made about any potential vertical vergence adjustments during fixations. In addition, Jainta, Blythe, Nikolova, Jones and Liversedge (2014) recently conducted a detailed investigation of disparities occurring during natural sentence reading. They reported that vertical disparities were of much smaller magnitude than horizontal disparities, and observed no significant change in vertical vergence during reading fixations. Jainta and colleagues suggested that the limited activation of the vertical vergence system during reading could be due to functional differences between horizontal and vertical disparities and disparity reducing mechanisms in relation to maintaining a single unified perception of the written text. Namely, while horizontal vergence movements in response to horizontal disparities are central for depth perception and stereopsis, vertical vergence movements are likely to have a sub-servient role in maintaining the global alignment between the two retinal inputs and ensuring a stable percept over which horizontal fusional processes can operate. Aside from the two abovementioned accounts, no studies so far have systematically investigated the motor fusional response to stereoscopically imposed vertical disparities during lexical processing.

Nevertheless, existing studies in non-reading tasks indicate that while serving complementary functions, horizontal and vertical vergence are considered as two different mechanisms (Howard & Rogers, 2012; Stevenson, Lott, & Yang, 1997). Research investigating the characteristics of vertical vergence revealed that when compared to its horizontal counterpart, it is limited in both amplitude and speed (Bharadvaj et al., 2007; Kertesz, 1981). Furthermore, Panum's fusion area has been shown to be elliptical in shape, that is, sensory fusion is possible over a larger range of horizontal disparities than vertical disparities, which is consistent with Jainta et al.'s (2014) findings (Fender & Julesz, 1967; Howard & Rogers, 1995; Schor & Tyler, 1981). This limitation in the vertical dimension is likely due in part to our reduced capacity for vertical vergence movements (Steinman et al., 2000). For example, early work by Perlmutter and Kertesz (1978) compared binocular responses to horizontal and vertical symmetric disparity presentations (i.e., when each monocular image is offset by an equal amount in opposite directions) and discovered differences in speed and amplitude between the two main motor fusional responses such that horizontal vergence movements were rapid and direction-appropriate, unlike vertical vergence movements. In addition, some studies have shown that horizontal vergence does not occur when a substantial amount of vertical disparity is present in a stimulus – and vice versa (Mitchell, 1970; Yang, FitzGibbon, & Miles, 2003). Even though the reported disparity ranges were quite large (about 2 deg for the vertical dimension), those studies lend support to Jainta et al's (2014) hypothesis regarding the sub-servient role of vertical vergence movements in the perception of depth and stereopsis and suggest that a global vertical alignment between the two retinal percepts is a necessary pre-requisite for successful horizontal fusion. Nevertheless, it is yet unclear if induced vertical disparity during lexical processing affects horizontal fusion or even global reading efficiency measures.

One study to experimentally increase disparity within the stimuli during lexical processing was conducted by Blythe et al. (2010). They used dichoptic presentation of single words with equal amount of horizontal offset (from 0 to 0.74 deg in total, or up to 2 character spaces), and reported that the measured vergence responses were rapid and direction-appropriate. Furthermore, Blythe et al. (2010) observed that when making a horizontal saccade onto a stereoscopic stimulus, participants targeted the preferred viewing location (O'Regan, 1981; Rayner, 1979) for an unfused letter string with a length equal to the combined length of the two monocular images. For instance, if a 6-letter word was presented independently to each eye with 2 character spaces of stereoscopic disparity, then the resulting letter string appeared 8 characters long on the screen. This is an important point to consider: it appears that when inducing horizontal disparity within single words, the disparate images were combined, but not fused prior to fixation. When addressing the question of binocular saccade programming in reading, Liversedge et al. (2006) also reported that conjugate movements in reading appear to be programmed on the basis of a combined signal sent to both eyes. Importantly, they did not introduce disparity in their stimuli, but simply presented different parts of a target word within a sentence individually to each eye (e.g. for the word *cowboy*, *cowb* was only seen by one eye and *wboy* was only seen by the other eye). Nevertheless, these two studies seem to suggest that saccades in reading are not programmed on the basis of independent input from each eye, but rather based on a combined percept of the dichoptic presentation. However, little research exists to clarify how the saccadic targeting system would respond to stereoscopically imposed vertical disparity during lexical processing.

We therefore set out to conduct a detailed investigation of vertical motor fusion in response to symmetric vertical offset during a lexical decision task. There were several aims to the study. Firstly, we were interested in the vertical vergence response to binocular image misalignment and its effect on lexical identification processes. Secondly, we investigated the sensitivity of saccade targeting mechanisms to vertical disparity in the parafovea. Finally, as a more specific exploration, we aimed to investigate the influence of the vertical stereoscopic disparity manipulation on a well-established finding in reading research: the frequency effect, or the increased efficiency of lexical processing for commonly occurring words (Inhoff & Rayner, 1986; Rayner, 1998; White, 2008). The theoretical motivation for this investigation is discussed in the context of the Interactive Activation (IA) model of word recognition (McClelland & Rumelhart, 1981). It is possible that the fusion of binocular inputs, both motor and sensory, is achieved at an earlier and separate stage of processing than lexical identification, prior to the feature extraction stage of the IA model. If that were the case, adding a level of complexity at the fusion stage of processing in the form of a disparity manipulation would cause an equal global increase in total

RTs for both HF and LF words. However, it is also possible that visual fusion interferes with the feature extraction stage of processing, as fusion is central for attaining high quality binocular visual information. Therefore, making feature extraction more difficult by imposing vertical disparity in the stimuli would initially slow down the processing of both HF and LF words, but at the following (letter and word) stages of lexical identification, HF words would be processed faster. In other words, there might be an interaction between the two factors, such that the cost of adding complexity at the visual fusion stage would be larger for LF than for HF words. An alternative possibility would be that when presented with induced disparities within the range of those observed in normal reading, the vertical vergence system would remain inactive, which would indicate that vergence responses to this type of disparity are quite different to those associated with horizontal disparities. This in turn would be consistent with the claims of Jainta et al. (2014), who argue that vertical disparities provide much less useful information for stereopsis than do horizontal disparities given the horizontal alignment of the two eyes in the human visual system.

Based on previous findings, we made several predictions. We expected that, similar to Blythe et al. (2010), introducing a level of processing complexity by inducing vertical image disparity in the stimuli would affect reaction times and accuracy in the lexical decision task. It would be necessary for participants to attain a stable unified percept of the dichoptic stimuli in order to make a lexical decision, and we expected that there would be a time cost associated with this. Furthermore, if participants found it impossible to fuse the imposed vertical disparities due to the vertical vergence limitations of the visual system, they would be unable to perform the lexical decision task, as it would be extremely difficult to distinguish the words from the non-words (Fig. 1; see also Blythe et al., 2010). Although we only attempted to actively drive vertical vergence, we expected that a small amount of horizontal vergence would likely be observed following a horizontal saccade. More critically, if the vertical disparity presentation triggered a vertical vergence response we would likely observe additional changes in horizontal fusional responses that typically occur in reading. In terms of saccadic programming, we expected that if saccades to dichoptically presented parafoveal targets were programmed on the basis of the individual input received by each eye, then that would be reflected in the direction and magnitude of the resulting fixation disparity. In other words, if the left dichoptic image was presented above the right dichoptic image, and assuming saccades were programmed independently for each eye, it could be expected that the resulting fixation disparity would be left-hyper (i.e. the left eye would be fixating above the right eye). An alternative possibility would be that binocular saccade programming is based on a fused representation of the vertically disparate target stimulus, meaning that the direction and magnitude of fixation disparity would not be affected by the presentation of the dichoptic images on the monitor. Finally, in terms of lexical processing, any potential interaction between the vertical disparity presentation and the lexical frequency manipulation would be informative as to the degree of interdependence between visual processes related to fusion and linguistic processes related to lexical identification. Such an interaction was observed in a recent study by Jainta, Blythe and Liversedge (2014), who found that the efficiency of lexical processing was diminished in monocular reading conditions. On the other hand, previous findings (Blythe et al., 2006; Juhasz et al., 2008) reported no influence of lexical frequency and orthographic manipulations on horizontal binocular disparity. Therefore, we explored whether vertical binocular disparity would interact with lexical processing, or if it would have an additive effect on total processing times for both high-frequency (HF) and low-frequency (LF) words.

2.2 Method

2.2.1 Participants

Participants were 8 native English speakers from the University of Southampton, who took part in the experiment in exchange for Psychology course credits, or payment at the rate of £6 per hour. All participants had normal or corrected to normal vision (with soft contact lenses) and no diagnosed reading difficulties. Testing their visual acuity with a Landolt C acuity chart confirmed that there were no considerable differences in acuity between the two eyes (best-corrected acuity in each eye was 20/20 or better at 4m). Additionally, a Titmus Stereotest indicated that all participants had functional stereopsis (minimal stereoacuity of 40 seconds of arc).

2.2.2 Apparatus

Binocular eye movements were measured using two Fourward Technologies Dual Purkinje Image (DPI) eye trackers, which recorded the position of both eyes every millisecond (sampling rate of 1000 Hz, spatial resolution < 1 min arc). Stereoscopic presentation of the target items was achieved through use of Cambridge Research Systems FE1 shutter goggles, which blocked the visual input received by each eye alternatively every 8.33 ms (corresponding to a 120 Hz refresh rate). The shutter goggles were synchronized with the eye trackers and interfaced with a Pentium 4 computer and a Philips 21B582BH 21” monitor. The experimental equipment made it possible to simultaneously track binocular eye movements whilst manipulating the unique visual input received by each eye. The monitor was situated at a viewing distance of 100 cm. To minimize head movements, participants leaned against two cushioned forehead rests and bit on an individually prepared bite bar.

2.2.3 Materials and Design

All participants viewed 208 trials, each consisting of a single 6-letter item. The item was either one of 52 high-frequency (HF) words (e.g., *summer*), one of 52 low-frequency (LF) words (e.g., *acumen*) or one of 104 non-words (e.g., *worzer*). Non-words were formed in a similar fashion to Blythe et al. (2010) by substituting a single letter in the center of a word and creating an obvious misspelling (e.g., *summer* to *sumxer*). The 52 HF items had an average frequency of 118.48 counts per million (ranging from 18 to 850) and the 52 LF items had an average frequency of 2.58 counts per million (ranging from 0 to 9), as indexed in the English language CELEX lexical database (Baayen, Piepenbrock, & Gulikers, 1995). A *t*-test confirmed that HF words were significantly more frequent than LF words, t (51) = 5.31, $p < .001$. All items were presented in red 20pt Courier New font on a black background. At the viewing distance of 100 cm, each letter height extended to 0.32 deg of visual angle. Each of the items was viewed by participants in one of four dichoptic presentation conditions: (1) aligned, where the two images were centered on the display monitor; (2) offset vertically by a total of 0.05 deg, (3) offset vertically by a total of 0.11 deg; (4) offset vertically by a total of 0.16 deg. The disparity presentation was symmetrical, i.e., the monocular images were offset by an equal amount in opposite directions in each eye. Conditions were counterbalanced such that every word appeared in each of the experimental conditions across participants. Additionally, whether the image presented to the left eye appeared above or below the image presented to the right eye was randomized and counterbalanced across conditions.

2.2.4 Procedure

The experimental procedure was approved by the University of Southampton Ethics and Research Governance Office and followed the conventions of the Declaration of Helsinki. Informed written consent was obtained from each participant after explanation of the procedure of the experiment.

Once participants were sat in front of the monitor, a monocular calibration procedure commenced (i.e., the left eye was occluded by the shutter goggle during calibration of the right eye, and vice versa). Participant were instructed to look at each of nine points in a 3x3 grid in a set sequence from the top left to the bottom right. Horizontal separation of the calibration points was 3.44 deg and the vertical separation was 1.26 deg relative to screen centre. Afterwards, the calibration was checked for accuracy and repeated if necessary. Once both eyes had been calibrated successfully, the experiment began.

Each trial consisted of a fixation point appearing on the left-hand side of the screen for 1 second, followed by the item (word or non-word) presented in the centre of the screen. The distance between the fixation point and the left edge of each stimulus/item was 2.54 deg visual angle (see *Figure 2*).

Participants were holding a button box, and were instructed to indicate by button press, as quickly and accurately as possible, whether the stimulus they saw was a word or a non-word. There were four practice trials to help participants become familiar and comfortable with the task. Calibration was checked for accuracy following every four trials and, if necessary, the eye trackers were recalibrated.

Figure 2. Dichoptic presentation of the experimental stimuli without fusion (left) and with fusion (right).

2.2.5 Data Analyses

Custom-designed software was used for the data analyses. Saccades and fixations were manually identified in order to avoid contamination by dynamic overshoots (Deubel & Bridgeman, 1995) or artefacts due to blinks. From the separate signals of the two eyes, we calculated the horizontal and vertical conjugate eye component [(left eye + right eye)/2; i.e., the version signal] and the horizontal and vertical disconjugate eye component [left eye – right eye; i.e., the vergence signal]. Several parameters of binocular coordination were calculated for each fixation period: (1) vertical fixation disparity at the start and end of fixations, where a value of 0 represents alignment of the two eyes at eye height; positive values represent left-hyper fixations and negative values represent right-hyper fixations; (2) horizontal fixation disparity at the start and end of fixation; a value of 0 represents alignment of the two eyes at the depth of the screen, positive values represent crossed fixations, where the point of fixation is in front of the screen, and negative values represent uncrossed fixations, where the point of fixation is behind the screen; (3) net vertical and horizontal drift in vergence (Jainta et al., 2010; Liversedge, White, et al., 2006; Nuthmann & Kliegl, 2009; Vernet & Kapoula, 2009), which is the change in fixation disparity between the beginning and the end of the fixation period and (4) total change in vertical and horizontal eye position between the beginning of the first fixation and the end of the final fixation on each item. In addition, we calculated total reaction time (RT) and total number of fixations for each item.

For data analyses, we used linear mixed-effects models (lmer from package lme4 (Pinheiro & Bates, 2000) in R (R Development Core Team, 2009). P-values were estimated using posterior distributions for the model parameters obtained by Markov Chain Monte Carlo sampling, which include a typical sample size of 10000 (Baayen, Davidson, & Bates, 2008). The model was applied to the non-aggregated data and participants and items were treated as random effects, while lexical frequency (HF vs. LF) and binocular image disparity (0 deg, 0.05 deg, 0.11 deg or 0.16 deg) were treated as fixed effects.

2.3 Results

In the following sections, we report a variety of analyses based on different eye movement measures. Approximately 1.5% of the data were excluded due to tracker loss, resulting in a total of 5657 fixations on which the following analyses are based. We begin by giving a short descriptive account of the overall findings from the lexical decision task (3.1), then focus on the initial reaction of the vergence system to our disparity manipulation (3.2), changes in disparity throughout the duration of an entire multiple fixation trial (3.3.) and cases where only one fixation was made per trial (3.4.). Before reporting further results regarding eye movement measures, it is important to clarify certain terms that will be used throughout the following sections. Binocular image disparity refers to the induced offset between the dichoptic images presented on the screen. Binocular fixation disparity refers to the differences in position between the left and the right eye in degrees of visual angle, as measured by the eye trackers.

Table 4. Descriptive data about lexical decision accuracy, total RTs, first fixation duration (FFD), single fixation duration (SFD) and mean number of fixations per trial (SDs in brackets). Disparity in the different conditions is reported in degrees of visual angle. Reading times are reported in milliseconds.

	Frequency	Disparity (deg)			
		0	0.05	0.11	0.16
Lexical decision accuracy	**HF**	100%	99%	99%	99%
	LF	92%	92%	93%	93%
	NW	97%	98%	98%	98%
Total RTs	**HF**	840.79 (22.23)	860.70 (23.16)	876.05 (23.11)	864.24 (22.48)
	LF	948.84 (30.05)	1082.37 (42.08)	998.53 (27.01)	1056.15 (37.91)
	NW	974.39 (20.27)	1015.50 (22.55)	1038.97 (24.49)	995.83 (24.13)
FFD	**HF**	407.32 (23.03)	393.01 (19.49)	414.57 (20.11)	371.73 (17.34)
	LF	374.74 (19.04)	369.03 (23.13)	405.29 (19.25)	378.81 (23.05)
	NW	399.41 (15.48)	380.71 (15.44)	401.20 (15.58)	362.49 (14.00)
SFD	**HF**	608.14 (31.35)	712.56 (65.00)	683.92 (46.73)	733.96 (48.00)
	LF	736.40 (170.27)	857.92 (98.16)	805.79 (66.16)	813.67 (75.12)
	NW	733.11 (54.89)	710.62 (69.00)	679.75 (55.50)	758.52 (60.64)
Number of fixations per trial	**HF**	2.41 (.07)	2.47 (.07)	2.42 (0.07)	2.45 (.07)
	LF	2.78 (.10)	2.87 (.11)	2.66 (.09)	2.85 (.11)
	NW	2.71 (.06)	2.77 (.07)	2.78 (.07)	2.79 (.07)

2.3.1 Lexical decision accuracy, reaction times (RTs) and number of fixations

The overall response accuracy in this experiment was 96%. Correct responses during lexical identification were taken as the behavioural indication that participants were able to successfully fuse the binocularly misaligned images. Table 4 contains information about participants' accuracy at the lexical decision task, mean RTs, fixation durations and number of fixations in all of the frequency and disparity conditions. Evidently, participants responded faster, made fewer fixations and were more accurate when identifying HF words than LF words and non-words.

To further explore the frequency effect, an LME analysis was applied to RT values with participants and items as random effects and frequency and binocular image disparity as fixed effects. The distribution of RTs was right-skewed, which is why a log-transformation was applied. The results revealed a significant effect of frequency: participants were faster at identifying HF words than LF words ($t = 4.24$, $p < .001$) and non-words ($t = 5.13$, $p < .001$), with no significant difference between the latter two ($t < 1$). The size of the frequency effect was approximately 145 ms on average. There was no effect of binocular image disparity ($t = 1.13$, $p = .24$) and the

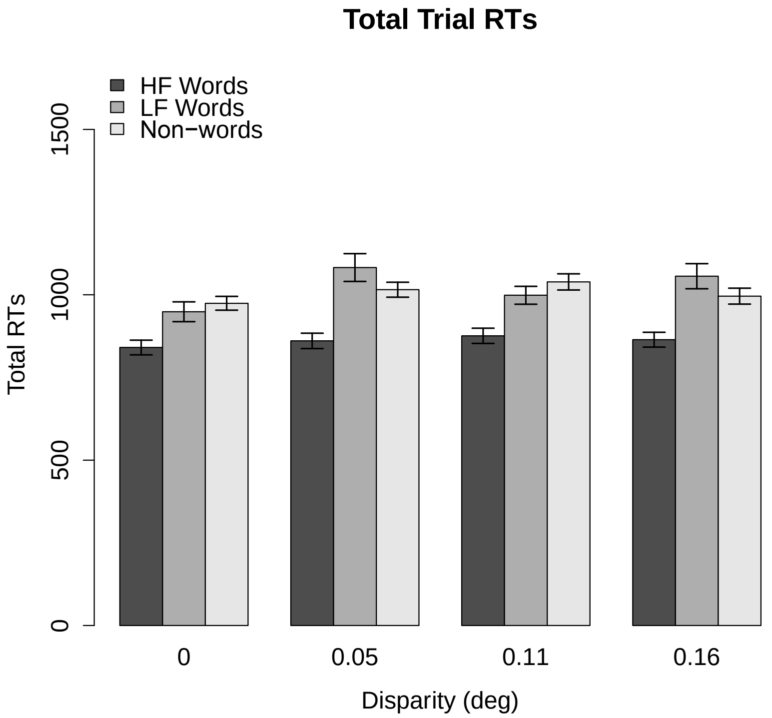

Figure 3. Mean total RTs (in milliseconds) in the different frequency and disparity conditions (HF: high-frequency words; LF: low-frequency words)

interaction between the two fixed effects was not close to significant (*t* < 1). These results are also summarised in *Figure 3*. Clearly, participants were able to perform the lexical decision task without any interference from the vertical disparity manipulation. The following sections explore this by focusing on vergence responses during fixations.

2.3.2 Initial reaction to vertical disparity

With regard to binocular landing positions, *Figure 4* represents the distribution of disparities at the start of the first fixation on each item, plotted onto a Cartesian coordinate system. Positive values on the x-axis denote crossed disparities, and positive values on the y-axis represent left hyper-vertical disparities (where the left eye is fixating above the right eye). Negative values on the x-axis correspond to uncrossed disparities, and negative values on the x-axis represent right hyper-vertical disparities (where the right eye is fixating above the left eye). The data clearly indicate that horizontal disparities were predominantly uncrossed, while vertical disparities were predominantly left-hyper.

Furthermore, we were interested in the sensitivity of the saccade programming system to vertical disparity in the parafovea. More specifically, we explored the relationship between the nature of the dichoptic presentation (left-hyper or right-hyper) and the resulting disparity at the start of each trial. A close correspondence between the two categorical variables would indicate that during the initial saccade onto the stimulus, each of the eyes targeted the monocular image presented to it separately via the shutter goggles. Evidence for such behaviour would hint at the possibility of independent monocular saccade targeting, as outlined by Liversedge et al. (2006a), which would in turn violate Hering's law of equal innervation. Our findings, however, indicate otherwise.

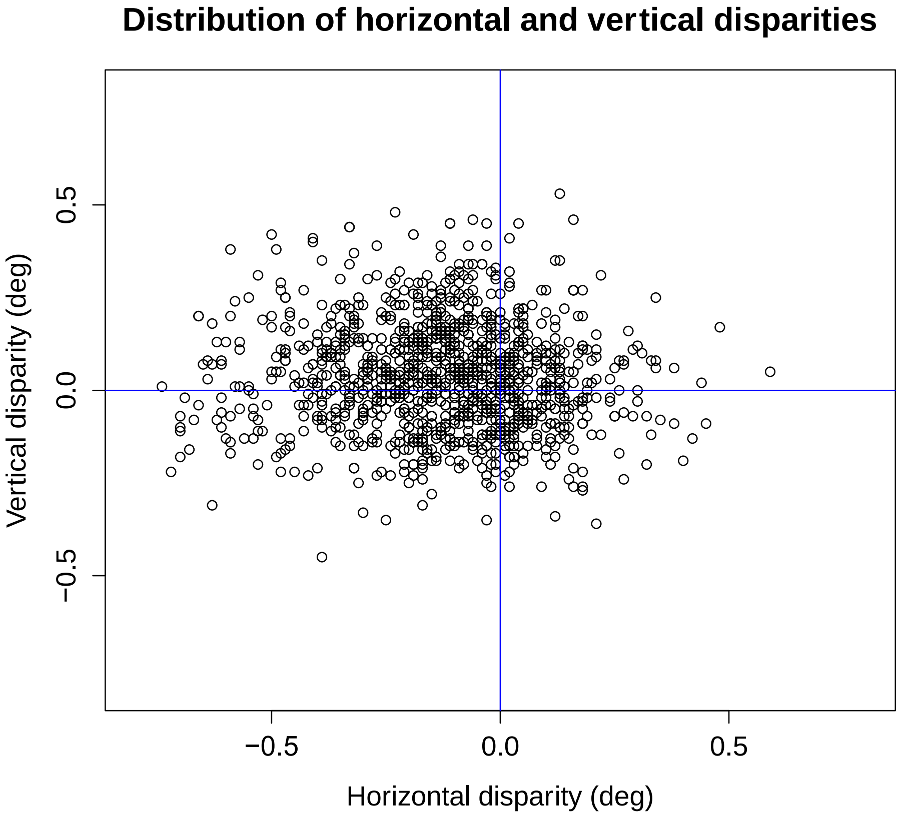

Figure 4. Horizontal and vertical disparities at the start of the initial fixation on each item plotted on a Cartesian coordinate system.

Recall that 75% of our stimuli were presented with some degree of vertical misalignment. Regardless of presentation condition, 38% of vertical disparities at the start of the initial fixation were right-hyper and 62% were left-hyper. A Chi-square test revealed that right-hyper and left-hyper disparities did not closely correspond to presentation conditions. In fact, left-hyper disparities were the predominant case, regardless of the binocular image manipulation (X^2 (1) = 15.10, p < .001). It appears that saccade landing positions when targeting a vertically misaligned lexical stimulus were not affected by the direction of presentation, as per Liversedge et al. (2006a).

The following part of the analyses focuses on how the vergence system responded when presented with a disparate image upon initial fixation on the target on trials with multiple fixations. We only included fixation disparities and fixation durations within 2SD of each participant's mean, which resulted in exclusion of approximately 3% of the data. 1375 fixations in total were analysed. *Figure 5* illustrates the distribution of horizontal and vertical disparities at the start (left) and at the end (right) of the initial fixation. The distribution of vertical disparities in both cases is clearly more leptokurtic, indicating that vertical disparities are generally smaller in magnitude than horizontal disparities. Fixation disparity at the start was not significantly affected by either lexical frequency, disparity manipulation or the interaction between the two (*t*s < 1, n.s.). Disparities at the end of fixations were also not influenced by either manipulation (all *p*s > .13). The average vertical disparity was 0.12 deg (*SD* = 0.09) at the start of the initial fixation and 0.11 deg (*SD* = 0.10) at the end of the fixation. A *t*-test revealed no difference in the drift in vertical fixation disparity throughout the fixation (*t* < 1). These results indicate that no considerable vertical vergence movements were made during the initial fixation on the target.

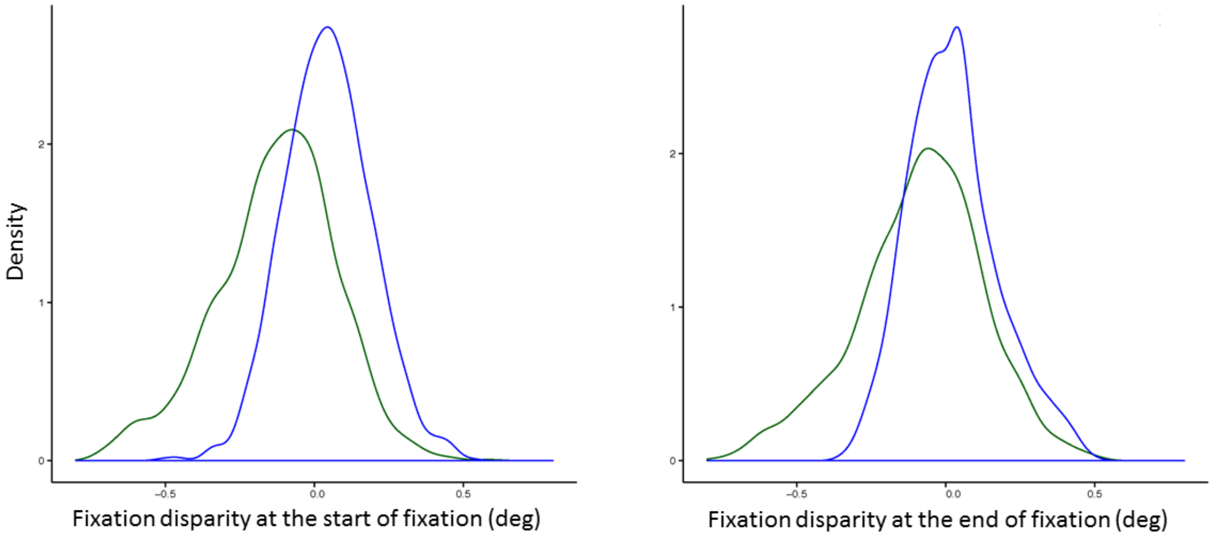

Figure 5. Distribution of horizontal (green) and vertical (blue) fixation disparity (in deg), measured at the start of fixation (left panel) and at the end of fixation (right panel).

Interestingly, however, we observed a small but significant change in horizontal disparity during the initial fixation. Horizontal disparities at the start of the fixation had an average magnitude of 0.18 deg (*SD* = 0.15), which was reduced to 0.16 deg (*SD* = 0.14) by the end of the fixation, *t* = 2.98, *p* < .01. A tendency for disparity-reducing vergence movements seemed to emerge as early as the first fixation on an item, even in the absence of any horizontal stereoscopic manipulation. This was not affected by either the frequency or the binocular image manipulation (*t*s < 1). Furthermore, there was no significant correlation between the magnitude of horizontal and vertical fixation disparities at the start or at the end of the initial fixation (*p*s > .19, n.s.). In other words, we observed a rapid horizontal vergence response during the first fixation on each item, following the horizontal saccade onto the stimulus, but no vertical vergence response to our disparity manipulation. The following sections further explore this pattern across all fixations made during a trial.

2.3.3 Reaction to vertical disparity throughout an entire trial

The previous sections demonstrate that the vertical and horizontal vergence system seem to make very different initial responses to parafoveal stereoscopic targets. Recall, however, that participants typically made more than one fixation on each item, hinting at the possibility that vergence movements occurred after the initial fixation. Therefore, a comparison was made between the start of the first fixation and the end of the final fixation on each multiple fixation item in order to capture any change in vergence throughout the duration of each trial. There was no significant difference in vertical fixation disparity between the two measures (*t* < 1, *p* > .16). In addition, an LME analysis investigated the magnitude of change in vertical fixation disparity between the start of the initial fixation and the end of the final fixation. There was no significant effect of lexical frequency, binocular image disparity, or the interaction between the two fixed factors (*t*s < 1). The average magnitude of vertical fixation disparity at the end of the final fixation on each item was 0.16 deg (*SD* = .13). Considering that the last fixation of each trial was the one during which participants pressed the button to indicate their lexical decision, this mean magnitude could be taken as an approximation of the amount of vertical fixation disparity which the visual system could easily tolerate in order to successfully process lexical information. Note, however, that no disturbances in fusion were reported by any of the participants, suggesting that the vertical limits of Panum's fusional area are likely larger than the reported value.

As for horizontal disparity, a consistent vergence response was observed throughout the duration of each trial: participants displayed a tendency for disparity-reducing vergence movements and a transition from uncrossed to aligned binocular disparities. This effect was significant (*t* = 4.12, *p* < .001), despite the absence of a stimulus that was intended to actively drive horizontal vergence. Horizontal disparities at the end of the final fixation on each trial were on average 0.02 deg smaller than they were at the start. In addition, an LME analysis confirmed that horizontal vergence measures at the end of each trial were not affected by the vertical disparity manipulation ($t < 1$), nor were they correlated with the magnitude of vertical fixation disparity, $r (1373) = .03, p = .29$. These findings support the previous statement that the horizontal and vertical vergence systems appear to respond differently and independently when processing misaligned lexical stimuli from the very first fixation on each item to the final one.

2.3.4 Single fixation trials

As a final step in our investigation, we explored cases in which only one fixation was made per trial. It was important to include single fixation trials in the analyses, as they would undoubtedly provide insight into any potential interactions between low-level visual processes involved in disparity processing and high-level lexical identification processing. In addition, cases in which vertical disparity was dealt with in a single fixation would enable us to closely monitor any potential vergence responses to our vertical manipulation. Note, however, that single fixations were made on only 17% of trials. Data were included in the analyses if fixation duration, horizontal and vertical disparities at the start and the end of fixations fell within 2 *SD* of each participant's mean. This resulted in 5% data loss – 240 fixations in total were analysed.

Reaction time data are presented in Table 4. A significant lexical frequency effect of 119ms was observed in single fixation trials, $t = 3.38$, $p < .001$. There was no significant effect of binocular image disparity or the interaction between the two fixed effects (*t*s < 1). Therefore, it appears that single fixation trials did not differ significantly from multiple fixation trials in terms of participants' responses during the lexical decision task. Again, it is evident from these results that although a robust frequency effect was observed in the data, it was not affected by the visual disparity manipulation. The single fixation analysis reinforces the point that low-level disparity processing and high-level lexical processing do not appear to interact during word identification.

As for disparity measures, the mean magnitude of vertical disparity was 0.12 deg (*SD* = 0.10) at the start and 0.11 deg (*SD* = 0.09) at the end of single fixation trials. No significant vertical vergence movements were observed throughout the fixation ($t < 1$). In addition, LME analyses revealed that vertical disparities at the start and the end of the fixations were not affected by the frequency manipulation ($t_{\text{start}} = 1.55$, $p = .12$; $t_{\text{end}} < 1$), the disparity manipulation ($t_{\text{start}} = 1.63$, $t_{\text{end}} = 1.54$, *p*s = .11) or the interaction between the two fixed effects (*t*s < 1). However, once again we observed a consistent disparity-reducing vergence response in the horizontal dimension. A tendency emerged for horizontal disparities to move from uncrossed to aligned throughout a fixation. The mean magnitude of disparity was 0.15 deg (SD = 0.13) at the start and 0.12 (SD = 0.10) at the end of the trial. Disparity was reduced by an average of 0.03 deg throughout the duration of the fixation, *t* = 3.97, *p* < .001. There was no significant correlation between the magnitude of horizontal and vertical disparity at the end of fixations (*r* (238) = .09, *p* = .19), and an LME analysis revealed no effect of the vertical disparity manipulation on horizontal disparity measures (*t* = 1.31, *p* = .19). Therefore, the single fixation data reported here provide further support for the prediction of independence between the horizontal and the vertical vergence system. These results demonstrate that participants made no vertical vergence movements in response to the vertical disparity manipulation on the screen, whereas horizontal disparity reducing vergence responses were present and consistent in the absence of a horizontal stereoscopic manipulation.

2.4 Discussion

Binocular coordination is critical to successfully attaining a fused stable representation of the visual environment, which is essential for performing a variety of tasks, including reading. Recent findings have begun to explore the role of binocularity in reading, the way it affects language processing and the relative importance of various binocular visual processes for written language comprehension (see Kirkby et al., 2010 for review). The present study adds to that growing literature by making an exploration of the role of vertical binocular disparities in lexical processing. We focused on investigating the motor fusional response to induced vertical misalignments in the parafovea and, upon fixation, its potential influence on horizontal vergence movements that typically occur following saccades in reading, and its effect on lexical identification.

Our findings revealed that when participants made a horizontal saccade onto a centrally presented stimulus with induced vertical disparity, no change was observed in the vertical vergence system. That is, participants did not make significant disparity reducing vertical vergence movements during the initial saccade, nor when first fixating on the target or even throughout the duration of a trial. Importantly, there was a clear dissociation between the presentation on the monitor and the perceptual experience of our participants. Their subjective reports did not indicate any experience of diplopia or visual disturbances, or any awareness of our manipulation. This is in direct contrast to the vergence responses to words presented with a horizontal disparity observed by Blythe at al. (2010). This was further evidenced by the high lexical decision accuracy in all disparity conditions, as well as the robust frequency effect we observed across single and multiple fixation trials.

Furthermore, we were interested in the sensitivity of the saccadic targeting system to disparity in the parafovea. Previous findings regarding horizontal disparity have revealed that the vergence system reacts actively to disparity from fixation onset, but makes no adjustments during saccades when stimuli are presented stereoscopically (Blythe et al., 2012, 2010; but see Kapoula, Eggert & Bucci, 1995). In addition, Liversedge et al. (2006a) found that saccades were targeted to stereoscopic lexical stimuli based on a combined percept, regardless of which constituent of the target word was available to which eye monocularly. Similarly, the present results indicated that landing positions on the vertically disparate stimuli were not affected by the direction of the visual presentation. That is, vertical disparities at the start of the initial fixation on the target were predominantly left-hyper, regardless of whether the left monocular image appeared above or below the right monocular image. The left-hyper predominance was also observed in trials where the dichoptic images were presented without disparity. In addition, the magnitude of vertical fixation disparity at the start or at the end of each trial was not affected by the magnitude of binocular image disparity present on the screen. Indeed, vertical disparities larger than 1 character space were only measured on less than 10% of fixations, regardless of the fact that in 75% of trials the vertically disparate stimuli exceeded the height of one character by up to 50%. Therefore, it appears that when presented with a relatively small magnitude of vertical disparity in the parafovea, participants performed parallel saccades in both eyes, regardless of the vertical disparity in the stimulus. That is to say, the two monocular dichoptic images on the screen did not appear to have been used as separate saccade targets for each eye.

Interestingly, we observed significant systematic horizontal vergence movements as early as the first fixation on the stimulus, even in the absence of a horizontal disparity manipulation. In other words, the horizontal motor fusional system was automatically activated following a horizontal saccade, as is typically observed in normal reading, whereas the vertical system showed no significant activation. Importantly, we found no correlation between the magnitude of horizontal and vertical disparity and drift measures, indicating that in the current study, the two systems did not interact during lexical processing. Furthermore, the LME analyses found no effect of the vertical disparity manipulation on horizontal disparity magnitude and drift measures. All these findings suggest that the horizontal and vertical vergence system react differently to imposed vertical disparities. Future studies would ideally investigate the interaction between horizontal and vertical vergence when disparities are induced in both dimensions simultaneously, as well as the degree of automaticity in horizontal vergence during sentence reading.

When contrasting our findings about vertical disparity patterns with those reported by Nuthmann et al. (2009), several points become immediately apparent. Firstly, we observed a larger proportion of exo (uncrossed) than eso (crossed) horizontal disparities, while Nuthmann and colleagues reported the opposite pattern. These differences in the direction of horizontal disparities, as reported in different studies, have been discussed in detail elsewhere (Kirkby et al., 2013). Importantly, it has been suggested that viewing conditions associated with different data acquisition techniques (e.g., light text over dark background or vice versa) amongst a variety of other factors might affect the pattern of horizontal disparities in reading. As for vertical disparities, we observed the same left-hyper predominance in all induced vertical disparity conditions as Nuthmann et al. (2009) observed during sentence reading. It appears, therefore, that vertical disparities that occur during language processing are much less sensitive to viewing conditions than their horizontal counterpart. Furthermore, our findings regarding the range of horizontal and vertical disparities over which fusion is possible are compatible with the notion of an elliptical pattern for Panum's fusional area, indicating that fusion operates over a limited range of vertical disparities and a larger range of horizontal disparities. More critically, the vertical motor fusional mechanisms showed limited activation, even in the presence of a disparity manipulation designed to elicit a vergence response. While these findings differ from Nuthmann et al.'s (2009) report of approximately equal magnitude of horizontal and vertical disparity in reading, the present data fit neatly with studies in non-reading tasks, which suggest that the vertical limitations in Panum's area are caused in part by the visual system's diminished capacity to compensate for vertical misalignments with disparity reducing vergence movements (Houtman, Roze, & Scheper, 1977; Steinmann et al., 2000). This is also consistent with Jainta et al.'s (2014) accounts of vertical disparity in normal reading, and suggests that the difference in activation between the two oculomotor systems may be due to the separate but complementary functions that they serve.

In addition, the functional differences between vertical and horizontal fusional mechanisms are particularly relevant to understanding of the interplay between visual and linguistic processes in the present experiment. Our findings indicated that word identification was not disturbed by the particular nature of the binocular presentation. We observed no interaction between lexical frequency and vertical disparity, but also found no additive effect of the disparity presentation on global processing times for HF and LF words. A robust significant frequency effect was observed, regardless of the magnitude of disparity present in the stimuli. These findings are different from those reported by Blythe et al. (2010), who found that increasing horizontal disparity also increased the time taken to make a lexical decision. Note, however, that the magnitude of disparity they introduced in their stimuli was larger that the present experiment. In addition, their study did not include a lexical frequency manipulation, and they only reported the effect of induced disparity on total trial viewing times. Jainta et al. (2014), on the other hand, observed that presenting text monocularly, rather than binocularly, significantly reduced the frequency effect for HF words. Although we are cautious when comparing data from natural reading and lexical decision experiments, what we can nevertheless glean from those findings is that in the present study, despite the disparity manipulation, participants were able to derive the benefits of binocular vision during word identification and display the well-documented increased efficiency of lexical processing for HF words. It is likely that a fused percept of our stimuli was obtained at an early stage of visual processing, possibly prior to the feature extraction stage of lexical identification. Furthermore, it may well be the case that induced vertical disparities of the magnitude typically observed in reading caused no disturbance in lexical processing because they are informative in a different way to horizontal disparities. As Jainta et al. (2014) suggested, this dissociation between the two oculomotor responses is very likely due to the physical arrangement of the visual system and the resulting effect on binocular coordination, the computation of depth and stereopsis.

In conclusion, the present study demonstrated that during lexical identification, the visual system responds differently to stereoscopic vertical disparity than it does to horizontal disparity. Our findings suggest that the visual system programs saccades to vertically misaligned lexical stimuli based on a fused percept attained at an early stage of processing, as indicated by the observed pattern of landing positions and the reported vergence and disparity measures. Further work is needed to investigate the response of the visual system to induced disparities in all directions during lexical processing in order to quantify the degree of interdependence between horizontal and vertical fusional mechanisms.

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Chapter 3: Investigating binocular advantages in reading using dichoptic moving window presentation techniques

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3.1 Introduction

Reading is a sophisticated uniquely human skill that requires the simultaneous operation and coordination of visual, oculomotor, attentional and linguistic processing systems. Recently, it has also been shown that binocular vision provides clear advantages for reading (Heller & Radach, 1998; Jainta, Blythe, & Liversedge, 2014; Jainta & Jaschinski, 2012; Sheedy, Bailey, Buri, & Bass, 1986). What is less clear, however, is how binocular vision and binocular coordination might influence foveal and parafoveal processing in reading, and, consequentially, what part they might play in the decision of where and when to move the eyes. In the present study, we addressed this issue by exploring how binocular advantages unfold throughout reading, in relation to both parafoveal pre-processing as well as foveal processing of words. In the following sections, we describe the theoretical relevance of this work in relation to the influences of foveal and parafoveal information on oculomotor control decisions, the allocation of attention during reading and the contribution of binocular coordination and binocular advantages to text processing prior to and during direct fixation. We then outline the design of a novel binocular dichoptic gaze-contingent eye tracking experiment and how it allows to selectively study the influence of binocular vision processes during different stages of text comprehension.

3.1.1 Oculomotor control and the allocation of attention during reading

During reading, the eyes typically perform a sequence of fast ballistic movements known as saccades, which serve to direct the gaze from one word to another (i.e. version eye movements). Saccades are followed by brief periods of relative stillness known as fixations (200-300ms on average in reading), during which visual information is encoded (Raney, Campbell, & Bovee, 2014; Rayner, 1998). These eye movements are a reflection of the ongoing cognitive processes underlying reading (Liversedge & Findlay, 2000). To a very significant degree, the psychological processes related to visual and linguistic processing of text determine the two most important aspects of eye movement control in reading: when and where to move the eyes. A number of research findings have demonstrated that the availability of both foveal (directly fixated) and parafoveal (upcoming in the direction of reading) information is crucial for fluent reading, and that each type of information plays a distinct role in eye movement control (Rayner & Pollatsek, 1987, 1989; Rayner, Pollatsek, Ashby & Clifton, 2012). Characteristics of the foveal word such as its length, its lexical frequency, predictability from context and semantic compatibility with the preceding text influence the speed with which it is processed (i.e. fixation duration), and therefore the decision of when to move the eyes away from it and onto another word in the sentence (Ehrlich & Rayner, 1986; Hyönä and Olson, 1995; Inhoff & Rayner, 1986; Liversedge, Rayner, White, Vergilino-Perez, Findlay, & Kentridge, 2004; Rayner & Duffy, 1986; Rayner, Liversedge, & White, 2006; Rayner, Liversedge, White, & Vergilino-Perez, 2003; Rayner, Yang, Schuett, Slattery, 2014; White, 2008; see Hyönä, 2011 & Rayner, 1998, for reviews). Interrupting foveal processing by visually degrading fixated words or masking them at fixation onset results in severe disruptions to reading, indicating the critical importance of a high-quality visual input in the fovea for text comprehension (Fine & Rubin, 1999; Legge, Ahn, Klitz, Luebker, 1997; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981).

When exploring the decision of where to move the eyes, it is important to first consider the allocation of attention during reading. Early research by McConkie and Rayner (1975, 1976) and Rayner (1975) examined the size of the perceptual span in reading, or the region from which readers obtain useful information during a fixation. This was done using the moving window paradigm, a gaze-contingent display change technique where a “window” of text with varying size is presented around the point of fixation and information beyond it is masked or visually degraded. The window moves on a fixation-by-fixation basis, so that equivalent amounts of unmasked text are available on each fixation. Many studies have found that, for readers of English, the effective visual field extends asymmetrically from 3-4 characters to the left of fixation (approximately the beginning of the fixated word) to 14-15 characters (approximately three words) to the right of fixation (Häikiö, Bertram, Hyönä & Niemi, 2009; Rayner, 1986; Rayner, Castelhano, & Yang, 2009; Schotter, Angele, & Rayner, 2012). The notable asymmetry of the perceptual span indicates that for reading in English, as well as other languages with similar orthography, the critical parafoveal region from which most information is obtained is to the right of the fixated word (i.e. corresponding to the direction of reading). Experimental manipulations interfering with the availability of information in that region, such as reducing the number of visible characters or making the parafoveal word disappear after fixation onset on the preceding word, have been shown to cause considerable disruptions to fluent reading (Liversedge, et al., 2004; Rayner et al., 2006; Rayner, Liversedge et al., 2003; Rayner et al., 2014). This disruption is likely the result of the visual manipulation interfering with a reader's ability to pre-process parafoveal information to the right of fixation. Indeed, a number of studies have demonstrated that prior to directly fixating a word, readers are able to extract information about its length, orthographic and phonological features and use that information in order to direct their saccades (Juhasz, White, Liversedge, & Rayner, 2008; McConkie & Rayner, 1975; Pollatsek & Rayner, 1982; Rayner & Bertera, 1979). Furthermore, there is a robust preview benefit associated with uninterrupted parafoveal pre-processing. For example, when a word is masked or presented incorrectly in the parafovea, processing times for that word increase once it is directly fixated relative to when the correct version is available for pre-processing (Blanchard et al., 1989; Hyönä et al.; 2004; Rayner et al., 1982). Therefore, uninterrupted pre-processing of information to the right of fixation is a core characteristic of fluent reading, as it both guides the decision of where to move the eyes and aids word identification during direct fixation. In summary, both foveal and parafoveal information appear to play a key part in the decisions of when and where to move the eyes during reading, and these findings have been incorporated into the most influential models of oculomotor control during text processing (e.g., SWIFT, Engbert, Longtin, & Kliegl, 2002; E-Z Reader, Reichle, 2011; Reichle, Rayner, & Pollatsek, 2003).

3.1.2 The role of binocular vision in reading

Humans typically make use of both of their eyes when they read, and processes related to binocular coordination play a key role in providing a single, unified perceptual representation of written text. For most tasks at close viewing distances - including reading – high-precision binocular vision and a stable, single percept are attained via the process of fusion, which incorporates two integral components: motor and sensory fusion (Pratt-Johnson & Tillson, 2001; Schor & Tyler, 1981). Motor fusion comprises of the physiological mechanisms of vergence. A number of studies have revealed that during text processing, the two visual axes are often slightly misaligned by more than one character space (Blythe et al., 2006; Blythe et al., 2010; Jainta, Hoormann, Kloke, & Jaschinski, 2012; Liversedge et al., 2006a, Liversedge et al., 2006b, Nuthmann and Kliegl, 2009; Nuthmann, Beveridge, & Shillcock, 2014; Vernet & Kapoula, 2009). This is mainly due to transient divergence that occurs during saccades: the abducting eye typically makes a larger, faster movement than the adducting eye (Collewijn et al., 1988, Hendriks, 1996, Yang &

Kapoula, 2009; Zee et al., 1992). This divergence results in fixation disparity at fixation onset. Vergence eye movements (i.e. fine-grained oculomotor adjustments) are then made during fixations to counteract these disparities and to maximise the degree of correspondence between the two retinal inputs, even in reading (Jainta & Jaschinski, 2012, Jainta et al., 2010; Leigh & Zee, 2006). Sensory fusion – a neurophysiological and psychological process – serves to combine the two independent retinal representations into a single unified percept in the visual cortex as a basic step for further processing (Howard & Rogers, 1995; Worth, 1921). Sensory fusion is only possible within a limited range of fixation disparities known as Panum's fusional area (Blythe et al., 2010; Schor et al., 1989; Steinman et al., 2000). Thus, for a large range of tasks including reading, motor fusion usually serves to reduce disparities and sensory fusion occurs when disparity falls within the functional fusional range (Jainta, Blythe, Nikolova, Jones, & Liversedge, 2014).

The degree to which fixation disparity and processes underlying binocular fusion play a part in oculomotor control and the pre-processing of parafoveal text during reading has been investigated in a number of recent studies. For example, Nuthmann et al. (2014) used a binocular moving window technique to explore binocular coordination when only a limited amount of text was visible to the right of fixation (i.e. reading with a binocular moving window extending from 14 characters to the left of fixation to 2 characters to the right of fixation). They postulated that under this asymmetric window condition readers might be able to unconsciously increase the magnitude of their fixation disparity in order to make more parafoveal information available for processing. While Nuthmann and colleagues demonstrated that reading was considerably impaired when only two characters were available to the right of fixation, they found only limited support for their hypothesis with respect to binocular coordination. These findings suggest that binocular fusion processes during a fixation are not immediately affected by visual manipulations of parafoveal information. Note also that a further constraint with their methodological approach was that despite the use of a binocular moving window, the visual content that was available to both eyes during reading was very comparable. The lack of a dichoptic presentation method prevented the possibility of directly controlling the information that was exclusively available to one eye but not the other.

With respect to the limits of Panum's fusional area in reading, Blythe et al. (2010) conducted an experiment where participants were presented with stereoscopic linguistic stimuli (words or non-words) with varying degrees of horizontal disparity in a lexical decision task. The authors postulated that lexical identification – and therefore accurate lexical decision – would only be possible if participants successfully fused the disparate stimuli (otherwise it would be impossible to distinguish between a word and a pronounceable non-word). The findings revealed that participants were able to make highly accurate lexical decisions when horizontal disparity was 0.37 deg of visual angle (approximately one character space), but when disparity increased to 0.74 deg (two character spaces) performance was at chance. Furthermore, while appropriate vergence movements were made during the initial fixation on the stimulus in order to reduce the imposed stereoscopic disparity, no vergence adjustments were made during the initial saccade onto the stimulus. Thus, the authors concluded that the effective fusional range for linguistic stimuli corresponds to approximately one character space, and that participants did not use parafoveal binocular image disparity cues in order to coordinate binocular targeting of their saccades.

Another detailed exploration of binocular saccadic targeting was conducted by Liversedge et al. (2006). In their experiment participants read sentences with compound target words presented dichopticly, such that each eye received a separate independent input (e.g. if the target word was “*cowboy*”, one eye only received the first half of the word “*cowb*” and the other eye only received the second half “*wboy*”; the remainder of the sentence was presented in full to both eyes). There were several possible ways in which saccadic targeting could operate under the experimental conditions: 1) each eye could target its own separate input, thereby suggesting independent, monocular control of saccades; 2) both eyes could target one of the word parts, thereby signifying suppression of one monocular input; 3) saccades could be targeted on the basis of the whole word, indicating that a unified percept was obtained prior to direct fixation. Indeed, the authors found that despite the dichoptic manipulation, saccadic targeting was identical to what is typically observed in normal reading: the eyes landed on the preferred viewing location (i.e. just left of the word center, Rayner, 1979; McConkie, Kerr, Reddix & Zola, 1988) of the whole word. The results demonstrated that saccades in reading are targeted towards a unified percept of the parafoveal word that is derived at an early stage of processing, prior to direct fixation.

In summary, the above studies demonstrate the important role of binocular coordination and binocular fusion in parafoveal pre-processing prior to direct fixation. Interestingly, with respect to processing of the fixated word, Juhasz, Liversedge, White and Rayner (2006) found a degree of dissociation between binocular coordination processes during a fixation and the lexical characteristics of the fixated word. They found that during normal sentence reading, while fixation times on high-frequency (HF) words were shorter than fixation times on low-frequency (LF) words, fixation disparity did not differ systematically between the two conditions. Therefore, in normal reading conditions where binocular fusion is achieved without difficulty, foveal processing of a fixated word appears to be primarily influenced by the cognitive demands associated with that word. This is also the key assumption of influential computational models of oculomotor control in reading (e.g. E-Z Reader, Pollatsek, Reichle, & Rayner, 2006; Reichle, 2010;

Reichle, 1998; Reichle, Rayner,& Pollatsek, 2003), which postulates that lexical processing is of primary importance in driving the forward movement of the eyes.

It is not clear, however, whether this is also the case when fusion is prevented, or when binocular information is not available. Binocular fusion is an important prerequisite for observing the advantages of binocular over monocular vision. For example, when visual input is binocular, luminance thresholds are lower and contrast sensitivities are higher (Blake & Levinson, 1977; Campbell & Green, 1965; Legge, 1984). Additionally, performance at orientation discrimination (Bearse & Freeman, 1994) and letter recognition tasks is superior relative to when input is monocular (Eriksen et al., 1966). A number of studies have also provided evidence of global binocular advantages in a more complex task such as reading (Heller & Radach, 1998; Jainta et al., 2014; Jainta & Jaschinski, 2012; Sheedy et al., 1986). Binocular visual presentation results in faster reading speed as well as fewer fixations and regressions compared to monocular presentation. More importantly, a recent study by Jainta, Blythe and Liversedge (2014) demonstrated that binocular advantages are also present in lexical processing. The authors implemented an adaptation of the boundary paradigm (Rayner, 1975) in order to study the binocular advantages in reading. They placed an invisible boundary before a target word within a sentence and altered visual presentation from binocular to monocular or vice versa once a reader’s eyes crossed the boundary. The target word was either a commonly occurring, easy to process, high-frequency (HF) word or a less common, more difficult, low-frequency (LF) word. The boundary manipulation created four visual presentation conditions for the target word: it could either be 1) previewed and fixated binocularly, 2) previewed and fixated monocularly, 3) previewed binocularly but fixated monocularly or 4) previewed monocularly but fixated binocularly. The authors found that the frequency effect on fixation times, which was present in binocular reading, was modulated in monocular reading, such that no significant differences were observed in processing times for high-frequency (HF) and low-frequency (LF) words. In addition, Jainta et al. (2014) observed a benefit of binocular relative to monocular text presentation in both parafoveal and foveal processing. That is, when a HF target word was monocularly presented in the parafovea but was fixated binocularly, or when direct fixation was monocular instead of binocular, processing of that word was slower relative to when binocular information was available either during preview or direct fixation. These findings provided a striking demonstration of the central role of binocular vision for efficient reading and word identification. What is less clear, however, is the extent to which binocular advantages for reading performance and word identification can be attributed entirely to the differences in binocular coordination (i.e. fixation disparity) when text is read with both eyes, relative to one eye.

3.1.3 The present experiment

In this context, the aim in the present study was to understand further the precise aspects of text processing that benefit from binocular vision, and to quantify the cost associated with monocular visual processing during encoding of both foveal and parafoveal words throughout sentence reading. We implemented a novel, dichoptic, gaze-contingent, moving window technique (McConkie & Rayner, 1975), which allowed us to directly control the visual presentation of foveal and parafoveal text to each eye separately, on a fixation-by-fixation basis. We programmed a window of monocular text to either (1) move with the eye across the sentence or (2) dynamically increase or decrease in the parafovea to the left or to the right of fixation contingent on gaze position. Instead of using a window sized based on a fixed number of character spaces, we used word boundaries to define the margins of the moving windows. For instance, in order to pinpoint the cost of monocular foveal processing, we programmed the window such that when the eyes moved from one word in the sentence to the next, each fixated word was presented monocularly, and all the other words in the sentence were presented binocularly. In contrast, to quantify the cost of monocular parafoveal processing (either to the right or to the left), we presented each fixated word binocularly and all words either to the right or to the left of the fixated word, respectively, were presented monocularly. Thus, the number of words presented monocularly (i.e. the size of the monocular moving window) changed dynamically on a fixation-by-fixation basis, contingent on the position of the eyes within the sentence. These dichoptic moving window conditions were compared with pure binocular and pure monocular reading in order to exclusively investigate the binocular advantage associated with foveal and parafoveal processing. We analysed measures of global sentence processing and binocular coordination in order to explore the selective influence of our manipulation on reading performance and visual processing. We also embedded a target word manipulated for frequency in our sentences and investigated any potential modulations of the frequency effect that might occur in the different presentation conditions.

Based on previous research**,** we predicted that monocular text presentation would cause considerable disruption to reading, which would be observed in sentence-level measures of eye movement behaviour, in binocular coordination measures (i.e. fixation disparity and vergence) and in target word processing measures (i.e. by means of modulation of the word frequency effect). Furthermore, we were interested in quantifying the cost of monocular foveal processing during reading relative to binocular foveal processing. Jainta et al. (2014) found that there was a substantial cost to the efficiency of lexical processing associated with monocular visual presentation when a word was directly fixated, even if that word had been previewed binocularly. We expected, therefore, a considerable level of processing difficulty to be associated with our gaze-contingent monocular presentation of the fixated word (relative to normal binocular viewing), with respect to global sentence processing, binocular coordination and target word identification. Finally, we investigated the cost associated with monocular input from the parafovea during sentence reading. Given previous findings that parafoveal monocular text causes impairment to reading, we predicted that a moving window in which words to the right of fixation were presented monocularly would affect global reading performance, even when, upon direct fixation, the word would be presented binocularly. Importantly, with relation to abovementioned findings regarding the asymmetry of the perceptual span, we predicted that the cost to processing at the sentence level would only be apparent, or at least would be far greater, when information to the right but not to the left of fixation was monocular.

3.2 Method

3.2.1 Participants

Participants were 20 native English speakers from the University of Southampton (6 males, 14 females, average age = 21.2 years, range = 18-25 years). Participants took part in the experiment in exchange for Psychology course credits or payment at the rate of £6 per hour. All participants had normal or corrected to normal vision (with soft contact lenses) and no diagnosed reading difficulties. There were no substantial differences in acuity between the two eyes (best-corrected acuity in each eye was 20/20 or better at 4m). Additionally, all participants had functional stereopsis (minimal stereoacuity of 40 seconds of arc). Participants were naïve to the purpose of the experiment.

3.2.2 Apparatus

Binocular eye movements were measured using two Fourward Technologies Dual Purkinje Image (DPI) eye trackers, which recorded the position of both eyes every millisecond (sampling rate of 1000 Hz, spatial resolution < 1 min arc). Dichoptic presentation of the stimuli was achieved through use of Cambridge Research Systems FE1 shutter goggles, which blocked the visual input received by each eye alternatively every 8.33 ms (in synchrony with a 120 Hz refresh rate of the display monitor). The shutter goggles were interfaced with the eye trackers, a Pentium 4 computer and a Philips 21B582BH 21 inch monitor. The monitor was situated at a viewing distance of 100 cm. To minimize head movements, participants leaned against two cushioned forehead rests and bit on an individually prepared bite bar.

Prior to the experiment, participants' visual acuity was tested both binocularly and separately for each eye using a Landolt-C acuity chart and stereoacuity was tested using a Titmus Stereotest.

3.2.3 Materials and design

Forty sentences with neutral content were presented, as well as YES/NO comprehension questions after 25% of trials. Sentences were presented in 14 pt red uppercase/lowercase Courier New font on black background in order to minimise dichoptic cross-talk (i.e. the "bleed-through" of visual input to the occluded eye, see also Jaschinski, Jainta, & Schurer, 2006). At the specified viewing distance, each letter subtended 0.25 deg of visual angle. On average, each sentence contained 76.63 (range = 72-86) characters. There were 12 words in each sentence, including a target word that was manipulated for lexical frequency. Target words were taken from the SUBTLEX-UK database (van Heuven, Mandera, Keuleers, & Brysbaert, 2014) and mean frequency was calculated using Zipf values: 5.01 Zipf on average for HF words (*SD* = 0.48) and 2.05 Zipf on average for LF words (*SD* = 0.58). HF and LF target word pairs were matched on word length (mean target word length = 5.75 characters). The words in each sentence were between four and eight characters long (mean word length = 6.38 characters). The full list of stimuli is presented in Appendix 1. We divided the sentences into five blocks and presented each block of eight sentences in one of five dichoptic gaze-contingent presentation conditions: (1) All words in the sentence were binocular. (2) Each fixated word was monocular, but all other words were binocular. (3) Each fixated word was binocular but all words to the right of fixation were monocular. (4) Each fixated word was binocular but all words to the left of fixation were monocular. (5) All words in the sentence were monocular. The sentences were presented in 5 blocks of 8 sentences (each block in a different presentation condition). A Latin Square design was used and the presentation order of blocks in different conditions was counterbalanced, such that across all participants, each sentence appeared in each condition with each version of the target word, but no sentence was repeated for any individual participant, and each participant saw the blocks in a different order. Monocular presentations were counterbalanced across the left and right eye.

3.2.4 Procedure

The experimental procedure was approved by the University of Southampton Ethics and Research Governance Office and followed the conventions of the Declaration of Helsinki. Informed written consent was obtained from each participant prior to the start of the experiment.

After participants had agreed to take part in the experiment, tests of visual acuity and stereo-acuity were conducted. We used a monocular calibration procedure to calibrate the eye-trackers (i.e., the left eye was occluded by the shutter goggle during calibration of the right eye, and vice versa). Participants were instructed to look at each of nine points on a 3x3 grid in a set sequence from the top left to the bottom right. Horizontal separation of the calibration points was 10 deg, and the vertical separation was 2 deg relative to screen centre. Afterwards, the calibration was checked for accuracy and repeated if the Euclidian distance between the recorded eye position and the actual position of each validation point on the screen exceeded 0.06 deg of visual angle. Once both eyes had been calibrated successfully, participants completed five practice trials in order to get accustomed to the task and the experimental setup. At the end of the practice trials, a full calibration/validation run was completed once again and the experiment began.

Each trial consisted of the following sequence of events. A fixation circle appeared on the centre of the screen for 1500 ms. Afterwards, another circle appeared on the left-hand side of the screen, marking the beginning of each sentence. Participants were required to fixate this circle. After 1000 ms, the fixation circle disappeared and a sentence was presented. Once the participant had finished reading the sentence, they pressed a button on a button box to indicate that they had finished reading the sentence. Comprehension questions were presented after 25% of the sentences and participants used the button box to make a YES/NO response. The next trial was initiated by the button press at the end of the sentence, or the YES/NO response. Calibration was checked for accuracy after every 4 trials and the eye trackers were recalibrated if necessary. A full calibration/validation run was performed before each new block of 8 sentences was presented. Participants were given a break halfway through the experiment, as well as additional breaks whenever required. The entire procedure lasted for approximately 45-60 minutes.

3.2.5 Data Analyses

Custom-designed software was used for the data analyses. Fixations and saccades were manually identified in order to avoid contamination by dynamic overshoots (Deubel & Bridgeman, 1995) or artefacts due to blinks. We excluded trials with track loss, fixations longer than 1200 ms or shorter than 80 ms, as well as the first and the last fixation on each trial. The following analyses were conducted on the remaining 86% of data (8891 fixations).

From the separate signals of the two eyes, we calculated the horizontal and vertical conjugate eye components [(left eye + right eye)/2] and the horizontal and vertical disconjugate eye components [left eye – right eye]. For all the analyses of fixation disparity and vergence drift we only analysed fixations where the measured fixation disparity fell within 2.5 standard deviations of the mean for each participant in each condition (<1% of the data were excluded). Thus, we were able to exclude any atypically large fixation disparities (e.g., bigger than 2 deg), which may have occurred as a result of tracker error. At the same time, basing the exclusion criteria around the performance of each participant in each condition, we retained the typically larger fixation disparities observed in monocular reading due to increased divergence of the occluded eye.

A linear mixed model is a powerful statistical technique which accounts for both fixed and random effect and allows for the inclusion of participants and items in the same analyses. For that reason, we constructed Linear Mixed-effect Models (LMMs) using the lmer program from package lme4 (version 1.1-11, Bates, Maechler, Bolker, & Walker, 2014) in R, an open-source programming language and environment for statistical computation (R Development Core Team, 2012). We used the lmerTest package to compute *p*-values (Kuznetsova, Brockhoff, & Christensen, 2016). Values for mean fixation duration, first fixation duration (FFD) and gaze duration (GD) were log-transformed prior to running the models due to the skewed right tails of their distributions. We report regression coefficients (*b*s), which estimate the effect size relative to the intercept, as well as standard errors (*SE*s) and *t*-values. Given the number of participants and observations per participant, the *t*-distribution will approximate the *z*-distribution; therefore we consider as statistically significant those cases where $|t| > 1.96$ (Baayen, Davidson & Bates, 2008). For binary dependent variables such as regression probability we used generalised linear mixed models (glmer function from package lme4) and report the Wald *z* and its associated *p*-value. For models with interaction terms we computed successive difference contrasts using the contr.sdif function from the MASS package (Venables & Ripley, 2002).

3.3 Results

Comprehension rate was at ceiling in all presentation conditions (mean accuracy = 98%). At the end of the experiment, we obtained subjective reports from each participant, asking about their visual experience. None of the participants were aware of the experimental manipulations. In fact, often participants did not believe that they had been reading monocular text at all, and asked us to repeat the viewing conditions after the experiment was completed to demonstrate that visual input to one of their eyes had been partially or entirely blocked during 80% of the trials. They were very surprised when we did this. This is a strong demonstration that in our sample of participants with normal vision, there was no immediate difference in perceptual experience between a binocular and a monocular visual presentation.

Below we report measures of global sentence processing, binocular coordination, and target word processing. In each subsection, we first estimate binocular advantages in reading by comparing binocular and monocular presentation conditions. We then compare each of our dichoptic moving window presentation conditions with binocular and monocular reading in order to demonstrate the effects of selectively restricting foveal and parafoveal processing to monocular visual input.

3.3.1 Global sentence processing measures

3.3.1.1 Comparison between binocular and monocular presentation.

When comparing binocular and monocular reading, we successfully replicated previous findings of binocular advantages for language processing in global measures of eye movement behaviour (see Table 5). Total sentence reading times were considerably shorter in binocular reading compared to monocular reading. Furthermore, monocular reading resulted in a significant increase in mean fixation duration, more fixations and more regressive saccades than in the binocular presentation condition. These results indicate that monocular text presentation substantially impaired reading.

3.3.1.2 Monocular foveal processing

For this portion of the analyses we compared the monocular foveal viewing condition with binocular and monocular reading. The results for global sentence processing revealed no difference in sentence reading times between binocular monocular foveal presentations. However, average fixation durations were longer in the monocular foveal condition compared to binocular reading (b = 0.02, SE = 0.02, t = 1.35, p = .08) and were in fact not significantly different from monocular reading ($t < 1$). As for the remaining measures (total sentence reading time, number of fixations and regression probability), we found no difference between binocular reading and the monocular foveal condition. It appears that whilst there was clearly a cost associated with restricting foveal processing to monocular input on a fixation-by-fixation basis, this level of disruption was not as great as was the case when the entire sentence was presented monocularly.

3.3.1.3 Monocular rightward parafoveal processing

When comparing the monocular parafoveal presentation to the right of the fixated word with binocular reading, we found no differences in mean fixation duration or regression probability (Table 5). We did, however, find a significant increase in total sentence reading times when text to the right of fixation was monocular, relative to binocular reading (b = 304.60, SE = 129.30, t =

2.34, *p* < .001). This increase in sentence reading time when text to the right of fixation was monocular was not significantly different from that observed when the entire sentence was presented monocularly (*t* < 1). Participants also made more fixations when parafoveal information to the right of fixation was monocular, compared to binocular reading (*b* = 1.01, *SE* = 0.41, *t* = 2.49, *p* = 0.04). This increase was again not significantly different from the increase observed in monocular reading (*t* < 1). These data clearly suggest that monocular presentation of parafoveal words to the right of fixation caused a similar degree of disruption to reading as when the entire sentence was presented monocularly.

3.3.1.4 Monocular leftward parafoveal processing

As a final step in the analysis, we investigated whether the cost associated with restricting parafoveal processing to monocular visual input was present exclusively when the direction of the gaze-contingent manipulation matched the direction of reading. We therefore compared reading with monocular parafoveal text to the left of the fixated word against binocular and monocular reading. We found that measures of global sentence processing did not differ significantly between this condition and binocular reading (Table 5).[1][2]

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[1] In order to rule out any potential practice effects, we also included trial order as a fixed effect in the LMEs. We found no effect of trial order for any of the reported measures (all *t*s < 1), supporting the idea that the experimental design did not influence the results.

[2] Each of the reported measures in Table 5 was entered as a dependent variable in a separate LME, with the following structure: *Model.Name = lmer(DV ~ Condition + (Condition|Participant) + (1|Item), data = DataFile).* The model for regression probability was computed as follows: *Model.Name = glmer(DV ~ Condition + (Condition|Participant) + (1|Item), data = DataFile, family = binomial)*

Table 5. Measures of global text processing. [3]

Variable name	Model estimates				Observed descriptive values	
Mean fixation duration	*b*	*SE*	*t*	*p*	Mean (ms)	*SD* (ms)
Binocular (intercept)	5.59	0.03	177.64	0.00	289	118
Monocular Foveal	0.04	0.02	2.34	0.03	298	115
Monocular Parafoveal Right	0.02	0.02	1.20	0.97	287	115
Monocular Parafoveal Left	0.00	0.02	-0.26	0.15	291	109
Monocular	0.06	0.01	3.29	0.00	306	117
Total Sentence Reading Time	*b*	*SE*	*t*	*p*	Mean (ms)	*SD* (ms)
Binocular (intercept)	3284.50	231.30	14.20	0.00	3299	1249
Monocular Foveal	195.50	153.21	1.28	0.12	3486	1310
Monocular Parafoveal Right	304.60	129.30	2.34	0.00	3641	1329
Monocular Parafoveal Left	207.90	152.90	1.36	0.16	3492	1434
Monocular	443.30	171.10	6.73	0.00	3813	1640
Total Number of Fixations	*b*	*SE*	*t*	*p*	Mean (ms)	*SD* (ms)
Binocular (intercept)	11.42	0.69	16.65	0.00	11.4	4
Monocular Foveal	0.33	0.48	0.70	0.44	11.71	4.07
Monocular Parafoveal Right	1.01	0.41	2.49	0.04	12.53	5.03
Monocular Parafoveal Left	0.78	0.54	1.49	0.15	12.33	4.54
Monocular	0.98	0.43	2.27	0.00	12.46	4.79
Regression probability	*b*	*SE*	*z*	*p*		
Binocular (intercept)	-1.13	0.37	-3.07	0.00		-
Monocular Foveal	0.05	0.09	0.40	0.68		-
Monocular Parafoveal Right	0.14	0.09	1.54	0.12		-
Monocular Parafoveal Left	0.11	0.10	0.83	0.41		-
Monocular	0.20	0.10	2.11	0.03		-

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[3] Each of the reported measures was entered as a dependent variable in a separate LME, with the following structure: *Model.Name = lmer(DV ~ Condition + (Condition|Participant) + (1|Item), data = DataFile)*. The model for regression probability was computed as follows: *Model.Name = glmer(DV ~ Condition + (Condition|Participant) + (1|Item), data = DataFile, family = binomial)*

3.3.2 Binocular coordination measures

Below we report findings regarding fixation disparity at the beginning and at the end of fixations, as well as proportion of aligned, crossed and uncrossed fixations. In accordance with previous research, aligned fixations were defined as those where both fixation points were within one character of each other within a word; crossed fixations were those where fixation disparity exceeded one character space and the left eye fixated further to the right than the right eye (eso); and uncrossed were those fixations where disparity exceeded one character space and the left eye was fixating further to the left than the right eye (exo). Fixation disparity measures and model parameters are reported in Table 6.

Table 6. Fixation disparity measures and model parameters.

Variable	Model Estimates			Observed descriptive values	
Disparity (start of fixation)	*b*	*SE*	*t*	|Mean| (deg)	|*SD*| (deg)
Binocular (intercept)	-0.23	0.04	233.11	0.25	0.16
Monocular Foveal	0.01	0.01	1.00	0.25	0.22
Monocular Parafoveal Right	0.09	0.03	2.80	0.17	0.13
Monocular Parafoveal Left	-0.04	0.04	-1.10	0.23	0.17
Monocular	-0.09	0.05	-2.00	0.31	0.20
Disparity (end of fixation)	*b*	*SE*	*t*	|Mean| (deg)	|*SD*| (deg)
Binocular (intercept)	-0.16	0.06	146.19	0.18	0.15
Monocular Foveal	0.01	0.01	0.86	0.19	0.20
Monocular Parafoveal Right	0.09	0.03	2.71	0.14	0.11
Monocular Parafoveal Left	-0.02	0.08	-0.26	0.18	0.15
Monocular	-0.11	0.05	-2.02	0.24	0.18

3.3.2.1 Comparison between binocular and monocular presentation

We replicated previous results relating to vergence behaviour during binocular reading (see Table 6). The average magnitude of fixation disparity in the binocular condition was 0.23 deg at the start of fixations, which is less than a character space. By the end of fixations, that disparity was significantly reduced to 0.16 deg ($t = -29.92$, $p < .001$). Critically, the magnitude of fixation disparity was significantly larger in monocular relative to binocular reading both at the start and at the end of fixation, a significant reduction in disparity was observed from start to end of fixation in the monocular condition ($t = -13.41$, $p < .001$).

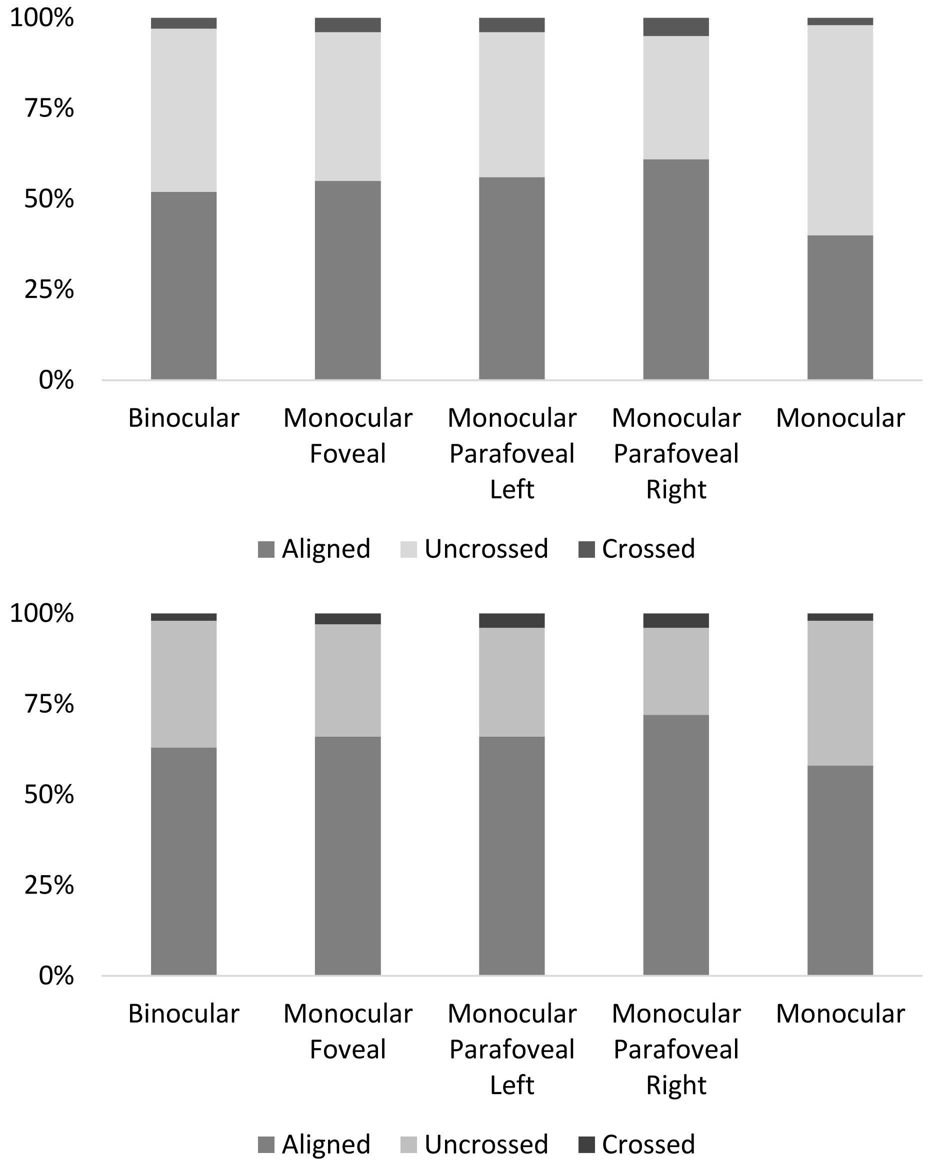

Figure 6. Proportion of aligned, uncrossed and crossed fixation disparity at the start (top) and at the end (bottom) of fixations.

We also replicated previously reported patterns of fixation disparity during binocular reading at the beginning and at the end of fixations (Blythe et al., 2010, Blythe et al., 2006, Liversedge et al., 2006a, Liversedge et al., 2006b). Disparities in the majority of fixations were aligned. Out of the remaining fixations, the majority of fixation disparities were uncrossed, and a small proportion were crossed. During monocular reading a smaller proportion of fixations were aligned at the beginning of the fixation period than in binocular reading, with uncrossed disparities accounting for the majority of misaligned fixations (see *Figure 6*). Those differences in proportion of misaligned fixations between the binocular and monocular presentation condition were significant for the start (*b*= .50, *z* = 5.75, *p* < .001) but not for the end of the fixation period (*b* = -0.06, *z* = -0.69, *p* = 0.50), suggesting that readers were able to compensate for the substantial initial misalignment that occurred for monocular fixations.

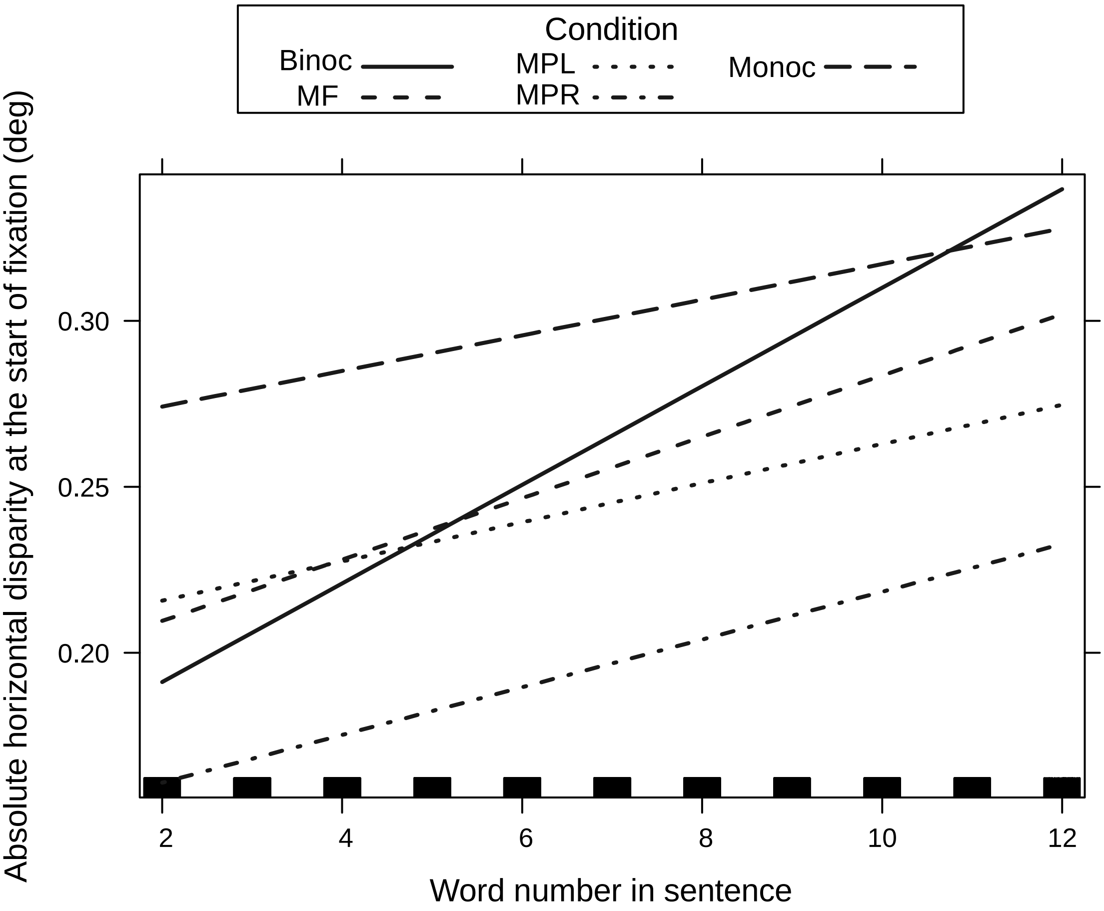

Figure 7. Interaction between fixation disparity at the beginning of fixations and the position of the eyes from left to right within the sentence.

Next, we were interested in how binocular coordination changed throughout each trial, both in the binocular and monocular control conditions and in the gaze-contingent conditions. We therefore examined how the absolute magnitude of fixation disparity at the beginning of fixations changed as a function of fixation position within the sentence from left to right and whether this varied between experimental conditions. In our comparison between binocular and monocular reading (i.e. our baseline conditions), we found a significant main effect of position within the sentence (*b* = 0.01, *SE* = 0.01, *t* = 10.43, *p* < .001) and a significant interaction between position and viewing condition (*b* = -0.01, SE = 0.01, *t* = -5.751, *p* < .001). As is evident from *Figure 7*, while fixation disparity magnitude in the binocular presentation condition tended to increase as the eyes moved from left to right along the sentence, it did so to a considerably lesser extent when reading was monocular. Similar findings were reported by Heller and Radach (1999) and Jainta et al. (2010). These results suggest that binocular coordination processes differ considerably between monocular reading both during a single fixation period and throughout an entire sentence reading trial.

3.3.2.2 Monocular foveal processing

With regard to fixation disparity, the magnitude of fixation disparity did not differ between binocular and monocular foveal presentation (see Table 6). There were no differences in the overall pattern of fixation disparities between binocular reading and the monocular foveal condition at the start of the fixation period (see *Figure 6*); there was, however, a significantly larger proportion of aligned fixations ($b = 0.76$, $z = 2.09$, $p = .021$) at the end of the fixation period in the monocular foveal condition. Further, there was a significant interaction between position within the sentence and visual presentation ($b = -0.01$, $SE = 0.00$, $t = -5.51$, $p < .001$). We found that an accumulation of fixation disparity occurred as readers moved from left to right, but the initial magnitude of disparity and the extent to which disparity increased was smaller than in binocular reading. This pattern differed considerably from monocular reading, indicating that although in the monocular foveal condition each fixated word was only presented to one of the eyes, binocular coordination processes remained efficient.

3.3.2.3 Monocular rightward parafoveal processing

The findings regarding fixation disparity were somewhat surprising. Firstly, when text to the right of fixation was monocular, the magnitude of fixation disparity was considerably reduced in comparison to binocular reading both at the start and at the end of the fixation period. Furthermore, when parafoveal information to the right was monocular, 72% of fixations were aligned at the start of the fixation period, which was a significantly larger proportion than fixations in binocular reading ($b = 0.94$, $z = 2.53$, $p = .002$). By the end of the fixation period the proportion of aligned fixations increased to 82%, which again was significantly different from binocular reading ($b = 1.22$, $z = 2.19$, $p = .012$). Furthermore, there was a significant interaction between viewing condition and position within the sentence ($b = -0.01$, $SE = 0.00$, $t = -3.724$, $p < .001$), such that when text to the right of fixation was monocular, initial fixation disparity magnitude was smaller than in binocular reading, and an accumulation of disparity occurred to a lesser extent (see *Figure 7*). Note that in this condition, participants started reading the sentence while only the first word that itself was under direct fixation, was presented binocularly, while all the other words in the sentence were presented monocularly. As the participants moved their eyes through the text, each newly fixated word was presented binocularly, until the final word of the sentence was fixated, at which point, all the words in the sentence appeared binocularly.

Thus, despite the fact that different proportions of the sentence were available to both eyes on each fixation, binocular coordination processes were not impaired.

3.3.2.4 Monocular leftward parafoveal processing

Binocular fixation disparity at the start and at the end of fixations when text to the left of fixation was presented to only one of the eyes did not differ significantly from binocular reading (see Table 6) . The proportion of aligned and misaligned fixations also did not differ significantly between the two conditions (*Figure 6*). Interestingly, we found a significant effect of fixation position within the sentence on absolute disparity magnitude (b = 0.01, SE = 0.00, t = 8.11, p < .001) and a significant interaction between fixation position and viewing condition (b = -0.01, SE = 0.00, t = -5.71, p = .005): it is evident from *Figure 7* that the increase in disparity magnitude as the eyes moved from left to right along the sentence was smaller when text to the left of fixation was monocular than in binocular reading. Note that in this dichoptic moving-window condition, when participants started reading a sentence all words aside from the fixated word were binocular. As participants moved their eyes through the text, words to the left of fixation were presented monocularly until only the final word in the sentence was binocular and all other words were monocular. This dynamic viewing situation, however, did not seem to interfere with efficient binocular coordination.

3.3.3 Target word analysis: the effect of lexical frequency

Recall that each sentence contained a target word manipulated for lexical frequency. Below we report first fixation durations (FFD) and gaze durations (GD) on the target word, as well as the number of first-pass fixations and number of regressions into the target region. Observed means and standard deviations are presented in Table 7. To estimate the differences between our different presentation conditions for the target word, we fit separate LMMs which estimated the effect of lexical frequency (HF vs LF target word), viewing condition and the interaction between the two for the 4 dependent variables: FFD, GD, number of first-pass fixations and number of regressions into the target region (see Table 8).

3.3.3.1 Comparison between binocular and monocular presentation

Table 7. Observed means (SD) for measures of target word processing for HF and LF words.

Variable	Frequency	Condition Binocular	MF	MPR	MPL	Monocular
Regressions into region	HF	0.13 (0.47)	0.19 (0.40)	0.32 (0.68)	0.30 (0.66)	0.24 (0.56)
	LF	0.69 (0.90)	0.48 (0.68)	0.45 (1.08)	0.76 (0.71)	0.94 (1.60)
Number of first pass fixations	HF	1.25 (0.48)	1.2 (0.45)	1.21 (0.41)	1.18 (0.43)	1.27 (0.45)
	LF	1.62 (0.90)	1.47 (0.89)	1.46 (0.76)	1.47 (0.78)	1.40 (0.63)
First fixation duration	HF	289 (121)	284 (85)	284 (91)	275 (136)	301 (105)
	LF	337 (120)	342 (138)	320 (128)	333 (138)	329 (159)
Gaze duration	HF	352 (155)	355 (230)	344 (146)	331 (197)	385 (197)
	LF	526 (276)	509 (322)	459 (242)	483 (310)	461 (271)

We found a significant main effect of lexical frequency in FFD and GD, though neither the effect of condition, nor the interaction between frequency and condition were significant. Similarly, we found that participants made more first-pass fixations on, and more regressions into LF than HF target words, but neither of those effects was modulated by presentation condition or the interaction between the two factors. These findings suggest that participants processed HF words faster than LF words in both binocular and the monocular presentation conditions. Nevertheless, Table 7 clearly shows a numerical reduction in the frequency effect in monocular relative to binocular reading: we observed a 20 ms reduction in the frequency effect in FFD and a 98 ms reduction in GD. These reductions in the frequency effect were not significant in FFD (b = 1.04, t = 0.03, p = .98), but were significant in GD (b = -112.89, t = -2.44, p = 0.03). In other words, under monocular compared to binocular viewing conditions GD was increased for HF words relative to LF words. This pattern of effects is similar to that reported by Jainta et al. (2014).

3.3.3.2 Monocular foveal processing

We found a significant effect of lexical frequency when foveal input was monocular in FFD and GD. Those effects did not differ from binocular reading (ts < 1). We did not find a significant effect of presentation condition or of the interaction between the two fixed factors. Similar to binocular reading, participants made more first-pass fixations and more regressions into the target region if the target was LF relative to HF, but neither effect was modulated by presentation condition or the interaction between the fixed effects (Table 8). In other words, when a target word was previewed binocularly but fixated monocularly, participants were able to process it as efficiently as they did in binocular reading.

3.3.3.3 Monocular rightward parafoveal processing

Similarly to the other conditions, we found a significant effect of lexical frequency in FFD and GD when text to the right of fixation was monocular. We also found an increase in the number of first-pass fixations and regressions into the target region for LF relative to HF target words. Neither of those effects was modulated by visual presentation, nor did we find an interaction between them. Finally, we explored whether participants were able to obtain a larger preview benefit if the target word was previewed binocularly rather than monocularly. We found no effect of preview condition in either FFD (b = 0.03, SE = 0.05, t = 0.53) or GD (b = 0.06, SE = 0.06, t = 0.94), suggesting that previewing the word monocularly did not affect fixation times when the word was directly fixated binocularly.

3.3.3.4 Monocular leftward parafoveal processing

We found that the significant effect of lexical frequency in FFD, GD, number of first-pass fixations and regressions into the target region did not vary as a function of condition or of the interaction between the fixed effects (see Table 8). Thus, lexical processing when text to the left of fixation was monocular was not impaired by the visual presentation.

Table 8. Model estimates for measures of target word processing.

	First fixation duration			Gaze Duration			Number of first-pass fixations			Regressions into target region		
	b	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*t*
Binocular (intercept)	5.67	0.05	104.01	5.76	0.08	75.57	1.38	0.06	23.89	0.55	0.12	4.50
Frequency (LF)	0.14	0.05	2.90	0.38	0.11	3.45	0.25	0.09	2.80	0.74	0.19	3.88
Presentation (monoc)	0.02	0.05	0.44	0.07	0.11	0.68	-0.13	0.09	-1.53	0.29	0.18	1.68
Frequency x Presentation	-0.04	0.11	-1.75	-0.23	0.16	-1.74	-0.27	0.17	-1.59	0.36	0.33	1.11
Frequency (MF)	0.14	0.04	3.49	0.39	0.11	3.49	0.25	0.09	2.82	0.60	0.14	4.40
Presentation (MF)	0.01	0.05	0.28	0.00	0.10	0.00	-0.11	0.09	-1.24	-0.07	0.12	-0.56
Frequency x Presentation	0.02	0.09	0.17	-0.05	0.15	-0.32	-0.12	0.18	-0.71	-0.25	0.19	-1.30
Frequency (MPR)	0.12	0.04	2.95	0.39	0.11	3.49	0.25	0.08	2.96	0.54	0.14	3.83
Presentation (MPR)	-0.01	0.05	-0.23	0.00	0.10	0.00	-0.11	0.08	-1.31	-0.03	0.12	-0.26
Frequency x Presentation	-0.07	0.09	-0.72	-0.05	0.15	-0.32	-0.15	0.16	-0.90	-0.43	0.20	-2.18
Frequency (MPL)	0.17	0.04	4.20	0.30	0.06	5.05	0.27	0.08	3.17	0.64	0.16	4.06
Presentation (MPL)	-0.02	0.05	-0.48	-0.10	0.06	-1.61	-0.13	0.08	-1.61	0.12	0.13	0.96
Frequency x Presentation	0.09	0.09	0.91	-0.01	0.13	-0.09	-0.10	0.16	-0.62	-0.09	0.24	-0.37

3.4 Discussion

The present research replicated previous findings of global binocular advantages in reading. Our results clearly demonstrate that when visual input is binocular, sentence processing is faster and readers make fewer, shorter fixations than when it is monocular. These findings are in accord with previous research (Heller & Radach, 1999; Jainta et al., 2014; Jainta & Jaschinski, 2012; Sheedy, Bailey, Buri, & Bass, 1986) and provide a further demonstration of the importance of binocular vision for the delivery of high-quality visual information necessary for fluent and efficient reading.

We then explored whether the binocular advantages observed in reading could be attributed to more efficient encoding of foveal information for binocular viewing, or more effective pre-processing of parafoveal information in binocular relative to monocular presentation conditions. Previous findings by Jainta et al. (2014) suggested that while binocular visual input both prior to, and during direct fixation on a word facilitates lexical processing, this facilitation is less pronounced when the word is monocularly fixated. We hypothesized, therefore, that restricting visual input to monocular information on a fixation-by-fixation basis would also result in considerable disruption to reading. Our findings were partially, but not entirely, consistent. We only observed a limited cost to processing in the monocular foveal condition, expressed in slightly longer mean fixation durations compared to binocular reading. That decrease in processing speed for the fixated words did not result in robust effects for total sentence reading time, nor did it result in a significantly increased rate of fixations and regressions. Our findings suggest, therefore, that when each word in a sentence is previewed binocularly but fixated monocularly, reading can proceed comparatively efficiently, relative to when larger portions of the sentence are presented monocularly. Critically, our results indicate that the considerable disruption to reading observed in the majority of eye movement measures in the monocular presentation condition cannot be attributed solely to disruption associated with encoding of foveal information. Instead, our data demonstrate that binocular input plays a key part in the efficient pre-processing of information to the right of fixation. As reported above, reading time increases and readers make more fixations when only monocular information is available in the parafovea to the right. In other words, binocular vision was associated with marked advantages in parafoveal pre-processing of upcoming text. Note also that we observed no differences between binocular reading and reading when text to the left of fixation is monocular, indicating that reading performance only suffered when binocular visual input was denied in the direction of reading. This finding is in line with previous studies (Liversedge et al., 2004; Rayner et al., 2003, 2006; Rayner et al., 2013), which have demonstrated that the critical region from which readers obtain information during reading of English and other languages read from left to right is to the right of fixation. Importantly, our results do not imply that there is a functional difference between the binocular fusion processes in the right and left visual field. They suggest, instead, that because in English more attention is allocated to text to the right of fixation than to the left, and because processing demands associated with that text guide eye movements, the need for a high-quality unified binocular input is more pronounced in the pre-processing of that text prior to direct fixation.

It is possible that the qualitative difference between a binocular and a monocular parafoveal presentation is such that when parafoveal input is monocular, the perceptual span is reduced. That is, the amount of useful information that readers extract during a single fixation may be influenced by the quality of the visual input. Although our experiment provides no direct evidence for this hypothesis, previous research by Legge, Ahn, Klitz, and Luebker (1997) and Legge, Cheung, Yu, Cheung, Lee and Owens (2007) has found that the visual span – the number of letters that can be reliably identified during a single fixation – to the left and to the right of the fixation point – varies as a function of certain stimulus characteristics, such as contrast. Alternative explanations, for example, that binocular visibility could yield higher visual acuity or facilitate inter-hemispheric transfer, are also plausible (though see Dehaene, Cohen, Sigman, & Vinckier, 2005 for further discussion). Further work is needed to test the different alternatives and to explore any potential differences in the size of the perceptual span – or indeed the degree to which readers can obtain useful information from text to the right of fixation – during binocular and monocular reading. To summarise, the present experiment replicated previous findings of binocular advantages in reading and demonstrated that, while binocular vision is important for the encoding of foveal information during reading, it plays a critical part in the efficient pre-processing of information to the right of fixation.

Aside from global reading behaviour, we also investigated the effect of our dynamic, gaze-contingent manipulations on binocular coordination. First, we replicated previous findings of binocular coordination in normal reading. When visual input was binocular, participants made predominantly convergent vergence movements in order to reduce fixation disparity throughout the fixation period. Fixation disparities that exceeded one character space were predominantly uncrossed (exo) and a small proportion were crossed (eso). This pattern of results is compatible with existing research (Blythe et al., 2010; Blythe et al., 2006; Jainta & Jaschinski, 2012; Jainta et al., 2009; Liversedge et al., 2006a, Liversedge et al., 2006b, though see Nuthmann & Kliegl, 2009 and Nuthmann et al., 2014 for a different pattern of results). It is important to note, though, that during monocular reading the magnitude of fixation disparity at the beginning of fixation was larger than during binocular reading, and although we did observe some reduction throughout the fixation period, monocular fixations remained significantly more disparate than binocular fixations (see also Jainta & Jaschinski, 2012). These findings are not surprising: under monocular viewing conditions, where a fusion stimulus is not present and there is no disparity feedback (open-loop), the occluded eye tends to diverge to a fusion-free vergence position termed the phoria (Howard & Rogers, 1995; Steinman et al., 2000). As a result, the observed disparity between the eyes is larger than in the binocular condition, where a fusion stimulus is present on each fixation. Our data demonstrate, furthermore, that during binocular reading there is an accumulation of fixation disparity as the eyes move from left to right throughout a sentence but that accumulation is not sufficient to disrupt fusional processes and cause diplopia (see also Heller & Radach, 1998; Nuthmann & Kliegl, 2009). Jainta et al. (2010) explained that this disparity accumulation throughout sentence reading is affected by each individual’s ability to compensate for saccadic disconjugacy. This was not the case in monocular reading, where the magnitude of fixation disparity was increased from the first fixation in the sentence and remained relatively unchanged as readers moved their eyes from left to right.

Out of all comparisons between the five viewing conditions, the most striking results with respect to binocular coordination emerged when text to the right of fixation was monocular. For this condition, there was a larger overall reduction in fixation disparity at the beginning and at the end of fixations than in binocular reading. In addition, a significantly smaller proportion of fixations in this condition had a disparity magnitude that exceeded one character space. Furthermore, the accumulation of disparity throughout the sentence, which was present in binocular reading, was significantly reduced when text to the right of fixation was monocular. Importantly, these effects were maintained even when we controlled for factors such as saccade amplitude, fixation duration and recalibration rate, all of which could potentially influence the magnitude of fixation disparity. These results do not lend support to theories suggesting that readers may be able to adaptively increase their fixation disparity in order to make more information available parafoveally (Nuthmann et al., 2014). It is possible that the dynamic characteristics of the visual presentation in our experiment affected binocular coordination. Recall that when text to the right of fixation was monocular, an increasing proportion of the sentence was presented binocularly during each forward fixation (i.e. while initially only the first word was binocular, more words to the left of fixation became binocular as the eyes moved from left to right). This continuous increase in the amount of binocular information available during each fixation may have resulted in a reduction in fixation disparity and an overall tighter coupling of the eyes. Another potential explanation for our findings may be related to binocular saccadic targeting. Recall that Liversedge et al. (2006a) established that saccades in reading are targeted towards a unified parafoveal percept achieved at an early stage of processing. Furthermore, Blythe et al. (2010) found that when a lexical stimulus was presented dichoptically with imposed horizontal binocular image disparity, participants targeted their saccades towards it on the basis of a unified – but not fused – percept (i.e. if a 6-letter word was presented in the parafovea with 2 characters of horizontal disparity, saccades towards it were programmed on the basis of an 8-letter stimulus). In other words, binocular image disparity in the parafovea did not trigger vergence movements or affect the coupling of the eyes during saccades, but only upon direct fixation. A monocular parafoveal preview, on the other hand, may provide a less ambiguous saccadic target than a binocular one, because it will not be affected by binocular image disparity by definition, since only one visual input will be available for parafoveal processing. It might have been the case, therefore, that in the present experiment a monocular preview to the right of fixation affected saccadic coupling, and this in turn caused the reduced transient divergence and a smaller magnitude of fixation disparity at fixation onset.

Critically, however, regardless of the precise cause for this improved saccadic coupling, the present results allow for an important distinction to be made between reading performance and the efficiency of binocular coordination processes. Although presenting text to the right of fixation monocularly was as disruptive to reading as an entirely monocular visual presentation, there was no cost to binocular coordination. That is, in contrast to monocular reading, the vergence system operated with a high degree of efficiency when text to the right of fixation was monocular (but the fixated word was binocular). These results indicate that there is dissociation between binocular coordination processes and reading performance when text to the right of fixation is monocular.

There may be two potential sources of difficulty with respect to the parafoveal pre-processing of monocular input. In the context of computational models of eye movement control, such as E-Z Reader, once a certain stage of lexical processing is reached for the fixated word, a reader's attention shifts to the following word, and if that word cannot be efficiently pre-processed, reading suffers. One potential explanation for the observed pattern of results is that the visual quality of the input to the right of fixation makes it difficult to extract useful features, such as orthographic information (though see Jainta et al., 2016 for further discussion). An alternative possibility is that the capacity with which parafoveal input is pre-processed may be reduced for monocular viewing conditions. That is, while attention is still allocated to words in the parafovea, the extraction of useful information is less efficient when those words are presented monocularly, rather than binocularly. This may be somewhat mitigated by the fact that the following direct fixation is binocular and word identification can operate in its optimal capacity. Indeed, in the present experiment, when parafoveal information to the right of fixation was monocular, but the fixated word was binocular, we observed a numerical but not significant increase in mean fixation duration. However, across the entire sentence trial, this difference in processing speed accumulated into a significant cost for total sentence reading times (and a considerable binocular advantage when parafoveal text was presented to both eyes).

These findings suggest that the considerable disruption to reading when text to the right of fixation was monocular was primarily associated with difficulties in the parafoveal pre-processing of upcoming text, and not with a diminished efficiency of binocular coordination.

As a final point of interest, we included a lexical frequency manipulation in our experiment in order to explore the effect of the different visual presentation conditions on word identification. Recall that Jainta et al. (2014) found that the robust frequency effect present in binocular reading was modulated when sentence presentation was monocular. Further, they observed an increase in the processing time for HF words when they appeared monocularly during either parafoveal preview or direct fixation. In contrast, the present study found a significant frequency effect across all presentation conditions. Nevertheless, when focusing only on purely binocular and purely monocular reading – the two conditions where visual presentation was identical across the two experiments – the pattern of our results is compatible with that reported by Jainta and colleagues. They found 44 ms frequency effect in FFD and a 45 ms effect in GD during binocular presentation. These effects were drastically reduced to 1ms in FFD and 8 ms in GD during monocular reading. In the present experiment, we found a 48 ms frequency effect in FFD and a 174 ms effect in GD during binocular reading, which were reduced considerably in monocular reading (28 ms in FFD and 76 ms in GD). This reduction in the frequency effect from binocular to monocular viewing conditions was statistically significant in GD in the present study, implying that the efficiency of processing for HF words suffered when reading was monocular. Thus, our findings map onto the pattern reported in previous research and suggest that an uninterrupted binocular input is an important prerequisite for efficient lexical identification. The differences in findings between the two experiments could potentially be due to the fact that Jainta and colleagues used a modification of the boundary paradigm (Rayner, 1975) whereby crossing an invisible boundary around the centre of each sentence switched visual presentation from binocular to monocular or vice versa. In contrast, the present experiment employed a gaze-contingent technique whereby visual presentation changed continuously, on a fixation-by-fixation basis and varying proportions of the text were binocular/monocular on each fixation. Secondly, while Jainta et al. (2014) presented their stimuli in randomised order, the present study used a blocked design. Taken together, these factors may have allowed for some degree of adaptation to occur across trials, thus contributing to a significant frequency effect in all presentation conditions. Future experimental work is necessary to test this possibility.

In conclusion, the present research explores the role of binocular vision for uninterrupted sentence reading. We used a novel, dichoptic, moving window, binocular, gaze-contingent change presentation technique and found that restricting foveal word processing during direct fixation to a monocular visual input did not cause a considerable disruption to reading. Instead, reading performance suffered when parafoveal information to the right of fixation was presented monocularly. These results indicate that binocular vision provides clear advantages for the pre-processing of upcoming, parafoveal text. Our findings speak to the complex interplay between the human visual system and the language comprehension system, which is fundamental for efficient reading performance.

Chapter 4: Binocular Advantages for Parafoveal Processing

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4.1 Introduction

Reading is a complex psychological task, involving rapid movements of both eyes in the same direction (saccades) from one word to the next, or, occasionally, backwards to previously encountered text (see Rayner, 1998, 2009 for reviews). During reading, as well as other visually demanding tasks, binocular coordination ensures that a stable, unified percept of the text is maintained across eye movements in order for visual processing to proceed without disruptions caused by diplopia (Blythe et al., 2006; Blythe et al., 2010; Jainta, Hoormann, Kloke, & Jaschinski, 2012; Liversedge et al., 2006a; Liversedge et al., 2006b; Nuthmann and Kliegl, 2009; Nuthmann, Beveridge, & Shillcock, 2014; Vernet & Kapoula, 2009). Recent findings have also indicated that binocular vision provides clear advantages for reading, such as shorter overall fixation and sentence reading times and an increased efficiency of word processing (Heller & Radach, 1998; Jainta, Blythe, & Liversedge, 2014; Jainta & Jaschinski, 2012; Sheedy, Bailey, Buri, & Bass, 1986). These advantages do not occur as a direct result of changes in the visual quality of the text, such as a reduction in contrast in monocular relative to binocular reading conditions but, rather, as a result of reduced efficiency in the word identification system when visual presentation is monocular relative to binocular (Jainta, Nikolova, & Liversedge, 2017).

Recent research findings have also suggested that binocular vision influences not only the speed with which words are identified in foveal vision, but also the efficiency with which readers process upcoming, parafoveal text, prior to direct fixation. Nikolova, Jainta, Blythe and Liversedge (2017) compared sentence reading performance in three different dichoptic gaze-contingent moving-window presentation conditions: 1) when only the fixated word (word *N*) was monocular and all other text was binocular; 2) when only words to the left of fixation (word *N-1* and beyond) were monocular and all other text was binocular; and 3) when only words to the right of fixation (word *N+1* and beyond) were monocular and all other text was binocular. They found that reading performance was largely unaffected in the first two conditions, but a considerable disruption to reading was observed when text to the right of fixation was monocular, even if the fixated word itself was binocular. They concluded that, during reading, binocular vision plays an important role for parafoveal pre-processing in reading. It is not yet clear, however, which particular aspects of parafoveal pre-processing benefit from binocular vision. Our main objectives in the present experiment were: 1) to quantify the spatial extent of parafoveal binocular visual input which is needed for uninterrupted reading; and 2) to establish whether binocular parafoveal visual input to the right of fixation is necessary for accurate saccadic targeting to, or for efficient pre-processing of, text to the right of fixation, or both.

Over the past 40 years, a large number of studies has investigated parafoveal pre-processing in reading using different gaze-contingent presentation techniques (McConkie & Rayner, 1975, 1976; Rayner, 1975), which allow the experimenter to manipulate in real-time the amount and/or type of printed information which is available around the point of fixation, contingent on fixation position. Using the gaze-contingent moving window paradigm, researchers have shown that in languages which are read from left to right, the perceptual span (the amount of useful information that can be extracted during a single fixation) extends from about 3-4 characters to the left of fixation (approximately the beginning of the fixated word) to about 13-14 characters to the right of fixation (approximately 2 words to the right of the fixated word; Häikiö, Bertram, Hyönä & Niemi, 2009; Rayner, 1986; Rayner, Castelhano, & Yang, 2009; Schotter, Angele, & Rayner, 2012). The fact that readers require this information in order to process text efficiently is an indication that, during natural sentence reading, gaze location and attention do not necessarily coincide: a reader may be fixating on one word but processing and planning a saccade towards an upcoming word. This is also a core theoretical assumption of the most influential models of eye movement control during reading (E-Z Reader, Pollatsek, Reichle, & Rayner, 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003; SWIFT, Engbert, Nuthmann, Richter, & Kliegl, 2005).

Importantly, readers undoubtedly benefit from this ability to attend to and pre-process parafoveal text prior to direct fixation. This has been demonstrated by a large number of studies using the gaze-contingent boundary paradigm (Rayner, 1975), in which an invisible boundary is placed in a sentence, usually in the blank space before a target word. The target word is then manipulated in some way (e.g., masked, misspelled, substituted with a different word, etc.). This experimentally manipulated preview of the target is available for the reader up to the point where they reach the pre-target word, but as soon as their eyes cross the invisible boundary, a display change is triggered and the correct version of the target word is presented. Thus, any manipulation of the target word is only ever available in parafoveal vision, as readers are not typically able to detect the display change (though see Slattery, Angele, & Rayner, 2011; Angele, Slattery, & Rayner, 2016). This experimental technique is among the most widely used in reading research and it has been extensively employed to study parafoveal pre-processing in reading (Rayner, 2014; Schotter et al., 2012; Vasilev & Angele, 2016).

One of the most robust and uncontroversial findings to have emerged from gaze-contingent boundary studies is that of a *preview benefit* effect, or shortened fixation times on a word for which valid preview information was available in the parafovea, prior to direct fixation (Rayner, 1998, 2009; Rayner, White, Kambe, Miller, & Liversedge, 2003; Vasilev & Angele, 2016). The critical importance of parafoveal pre-processing was compellingly demonstrated in a series of disappearing text studies (Liversedge, Rayner, White, Vergilino-Perez, Findlay, & Kentridge, 2004; Rayner, Liversedge, White, & Vergilino-Perez, 2003; Rayner, White & Liversedge, 2006). The authors found that if the fixated word (henceforth referred to as word *N*) was masked or disappeared 60 ms after fixation onset, reading proceeded without interruption, whereas if the word to the right of the fixated word (henceforth referred to as word *N+1*) disappeared during fixation on word *N*, reading performance was considerably disrupted. These findings suggest that during reading, while word identification processes are more efficient inside foveal vision than outside it (Bouma, 1973; Lee, Legge, & Ortiz, 2003), parafoveal pre-processing, to a very large degree, plays a critical role in fluent reading.

One important but under-investigated factor that contributes to a reader's ability to efficiently pre-process parafoveal text is the availability of binocular visual input to the right of fixation. In fact, Nikolova et al.'s (2017) findings are reminiscent of the abovementioned disappearing text studies, in that a significant cost to reading was observed when parafoveal text was presented monocularly. But while it is apparent that removing binocular visual input to the right of fixation hinders fluent reading, the underlying mechanisms of that effect are not well understood. In order to explore them, it is necessary first of all to consider the ways in which parafoveal text informs normal sentence reading. Research has suggested that parafoveal text to the right of fixation in reading is used for two main purposes with respect to eye movement control: to guide *where* the eyes move, and *when* the eyes move. The *where* decision relates to saccadic targeting: while a reader is fixating on word *N* (and processing it in foveal vision), they are able to direct their attention to upcoming text and accurately target their next saccade to a word in the parafovea (typically, but not always, word N+1). Evidence for this comes from the fact that readers of English – as well as other languages where individual word units are visually salient – make use of word length information and inter-word spacing cues in the parafovea (Inhoff, Liu, Starr & Wang, 1998; Morris, Rayner, & Pollatsek, 1990; Paterson & Jordan, 2010; Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner, 1979; Rayner, Fischer, & Pollatsek, 1998). This coarse, low spatial frequency, visual information is used to guide the eyes towards the preferred viewing location (PVL, Rayner, 1979) – slightly to the left of the centre of a word.

While parafoveal information is undoubtedly used for optimal saccadic targeting, it can also be used to guide *when* the eyes move by aiding word recognition processes. Readers can integrate information obtained from parafoveal previews with information obtained during direct fixation (Pollatsek, Lesch, Morris, & Rayner, 1992; Rayner, 1975). For example, they can extract orthographic (Balota, Pollatsek, & Rayner, 1985; Briihl & Inhoff, 1995; Drieghe, Rayner, & Pollatsek, 2005; White, Johnson, Liversedge, & Rayner, 2008) and phonological (Ashby & Rayner, 2004; Liu, Inhoff, Ye, & Wu, 2002; Miellet & Sparrow, 2004; Pollatsek, Lesch, Morris, & Rayner, 1992) information from the parafovea in order to aid lexical identification during direct fixation. Recent findings have also indicated that syntactic context can also influence parafoveal word recognition by generating grammatical expectations for upcoming words (Brothers & Traxler, 2016). There is also some evidence to suggest that readers may be able to access semantic information in the parafovea. For example, Schotter and Jia (2016) and Veldre and Andrews (2016) recently observed a benefit from previews that were visually dissimilar from the target word, but were semantically related and plausible from the preceding sentence context (though see also Brothers, Hoverston & Traxler, 2017). Since parafoveal information in reading can be used both to facilitate saccadic targeting and to aid word recognition processes, it is now important to establish which of these two functions is reliant on binocular visual input in order to operate efficiently. A disruption in either – or both – could potentially explain the effects observed by Nikolova et al. (2016). If monocular visual input to the right of fixation causes increased difficulty for saccadic targeting processes, or if it reduces the efficiency of pre-processing of parafoveal text for the purposes of word recognition, then an overall disruption to reading would be observed.

We developed a version of the dichoptic gaze-contingent moving window technique introduced by Nikolova et al. (2016) and applied it to the investigation of parafoveal pre-processing during sentence reading. We created three gaze-contingent conditions for parafoveal text. In each of these conditions, the fixated word was always entirely binocular, but the amount of binocular text to the right of the fixated word varied on a fixation-by-fixation basis: 1) one binocular character, 2) one binocular word, or 3) two binocular words. We compared the different binocular moving window conditions with entirely binocular and entirely monocular control presentations.

To reiterate, our first objective was to determine the spatial extent of the parafoveal region in which a binocular input is necessary for undisrupted reading, by identifying the experimental condition in which reading behaviours reach asymptote performance (when compared against the full binocular condition). We predicted that increasing the amount of binocular information to the right of fixation available for parafoveal pre-processing would improve reading performance, similar to previous findings (Jainta et al., 2014, 2016; Nikolova et al., 2016).

Our second objective was to determine whether saccadic targeting, or lexical processing, or both, were the primary mechanism via which binocular vision might influence reading performance. In one case, if the disruption to fluent reading from monocular parafoveal input were caused by the reduced efficiency of word identification processes then, under conditions of insufficient binocular parafoveal input, we would expect to observe an early effect on local-level measures of word processing (e.g., first fixation duration, gaze duration). Processes related to the identification of words are the primary “engine” that drives the eyes forward, according to the most influential computational models of eye movement control in reading (Engbert et al., 2005; Pollatsek et al., 2006; Reichle et al., 1998; Reichle et al., 2003). These effects on word processing, when summed across all of the words in a sentence, would also be expected to contribute to an overall increase in sentence reading times.

Alternatively, if the disruption to reading associated with monocular parafoveal input were primarily caused by oculomotor factors related to saccadic targeting, then we would expect to see these effects in measures of saccadic targeting accuracy. Such disruptions might result from the fact that visual acuity in the parafovea is considerably reduced compared to foveal vision (Rayner, 1998), and relying on one parafoveal visual input instead of two (monocular vs. binocular reading) may prove an additional source of difficulty for accurately selecting potential parafoveal saccadic targets (e.g., specific landing positions within words). Indeed, it has been demonstrated that, during reading, dynamic adjustments in saccadic targeting can occur and can vary as a function of parafoveal pre-processing (Liu, Reichle, & Li, 2014). If this were the case, then restricting binocular input to the right of fixation would affect saccadic landing positions, as well as affecting other key characteristics of saccades such as duration, amplitude and peak velocity (Leigh & Zee, 2006).

Finally, it is important to note that these two sets of predictions are not mutually exclusive. Indeed, parafoveal information is crucial to fluent reading because it influences the decision of both where and when to move the eyes (McConkie, Kerr, Reddix, & Zola, 1988). It may be the case, therefore, that binocular vision provides advantages for both word processing and saccadic targeting. Thus, restricting parafoveal binocular visual input would be expected to influence both word processing measures and saccadic targeting measures.

4.2 Method

4.2.1 Participants

Participants were 20 native English speakers from the University of Southampton (6 males, 14 females; average age = 21.2 years, range = 18-27 years). Participants took part in the experiment in exchange for Psychology course credits or payment at the rate of £6 per hour. All participants had normal or corrected to normal vision (with soft contact lenses) and no diagnosed visual or reading difficulties. To confirm that participants had normal vision, prior to the experiment we tested their visual acuity both binocularly and separately for each eye using a Landolt-C acuity chart. Stereoacuity was tested using a Titmus Stereotest. There were no substantial differences in acuity between the two eyes (best-corrected acuity in each eye in decimal units was 1.0 or better at 4m). Additionally, all participants had functional stereopsis (minimal stereoacuity of 40 seconds of arc). Heterophoria was measured with a Maddox Rod test at near (33 cm). The average horizontal deviation across all participants was 1.50 prism dioptres (*SD* = 1.71), and only six participants had a vertical deviation, with an average of 1.28 prism dioptres (*SD* = 0.48). Participants were naïve to the purpose of the experiment.

4.2.2 Apparatus

Binocular eye movements were measured using two Fourward Technologies Dual Purkinje Image (DPI) eye trackers, which recorded the position of both eyes every millisecond (sampling rate of 1000 Hz, spatial resolution < 1 min arc). Dichoptic presentation of the stimuli was achieved through use of Cambridge Research Systems FE1 shutter goggles, which blocked the visual input received by each eye alternatively every 8.33 ms (in synchrony with a 120 Hz refresh rate of the display monitor). The shutter goggles were interfaced with the eye trackers, a Pentium 4 computer and a Philips 21B582BH 21 inch monitor. The monitor was situated at a viewing distance of 100 cm. To minimize head movements, participants leaned against two cushioned forehead rests and bit on an individually prepared bite bar.

4.2.3 Materials and design

Sixty sentences with neutral content were presented, as well as YES/NO comprehension questions after 25% of trials (see Appendix B). Sentences were presented in 14 point red uppercase/lowercase Courier New font on black background in order to minimise dichoptic cross-talk (i.e., the “bleed-through” of visual input to the occluded eye; see also Jaschinski, Jainta, & Schurer, 2006). At the specified viewing distance, each letter subtended 0.25 deg of visual angle.

On average, each sentence contained 76.63 (range = 72-86) characters. There were 12 words in each sentence, and words were between four and eight characters long (mean word length = 5.68 characters). We divided the sentences into five blocks and presented each block of twelve sentences in one of five dichoptic gaze-contingent presentation conditions: (1) all words in the sentence were binocular (full binocular control); (2) the fixated word (word *N*) and two words to the right of fixation (word *N+1* and word *N+2*) were binocular, but all other words were monocular (two-word window, approximately 3 deg); (3) word *N* and word *N+1* were binocular, but all other words to the right of fixation were monocular (one-word window, approximately 1.5 deg); (4) word *N* and the first character of word *N+1* were binocular, but other characters in word *N+1* and all other words to the right of fixation were monocular (one-character window, approximately 0.25 deg); (5) all words in the sentence were monocular (full monocular control). A Latin Square design was used and the presentation order of blocks in different conditions was counterbalanced such that, across all participants, every sentence appeared in each condition, but no sentence was repeated for any individual participant, and each participant saw the blocks in a different order. Monocular presentations were counterbalanced across the left and right eye.

4.2.4 Procedure

The experimental procedure was approved by the University of Southampton Ethics and Research Governance Office and followed the conventions of the Declaration of Helsinki. Informed written consent was obtained from each participant prior to the start of the experiment.

After participants had agreed to take part in the experiment, tests of visual acuity and stereo-acuity were administered. We used a monocular calibration procedure to calibrate the eye-trackers (the left eye was occluded during calibration of the right eye, and vice versa). Participants were instructed to look at each of nine points on a 3x3 grid in a set sequence from the top left to the bottom right. Horizontal separation of the calibration points was 10 deg, and the vertical separation was 2 deg, relative to screen centre. Afterwards, the calibration was checked for accuracy and repeated if the Euclidian distance between the recorded eye position and the actual position of each validation point on the screen exceeded 0.06 deg of visual angle. Once both eyes had been calibrated successfully, participants completed five practice trials in order to get accustomed to the task and the experimental setup. At the end of the practice trials, a full calibration/validation run was completed once again and the experiment began.

Each trial consisted of the following sequence of events. A fixation circle appeared on the centre of the screen for 1500 ms. Afterwards, another circle appeared on the left-hand side of the screen, marking the beginning of each sentence. Participants were required to fixate this circle.

After 1000 ms, the fixation circle disappeared and a sentence was presented. Once the participant had finished reading the sentence, they pressed a button on a button box to initiate the presentation of the following sentence. Comprehension questions were presented after 25% of the sentences and participants used the button box to make a YES/NO response. Calibration was checked for accuracy after every four sentences and the eye trackers were recalibrated if necessary. A full calibration/validation run was performed before each new block of 12 sentences was presented. Participants were given a break halfway through the experiment, as well as additional breaks whenever required. The entire procedure lasted for approximately 45-60 minutes.

4.2.5 Data Analyses

Custom-designed software was used for the data analyses. Fixations and saccades were manually identified in order to avoid contamination by dynamic overshoots (Deubel & Bridgeman, 1995) or artefacts due to blinks. We excluded trials with track loss, fixations longer than 1200 ms or shorter than 80 ms, as well as the first and the last fixation on each trial (<2% of fixations).

From the separate signals of the two eyes, we calculated the horizontal and vertical conjugate eye components [(left eye + right eye)/2] and the horizontal and vertical disconjugate eye components [left eye – right eye]. For all the analyses of fixation disparity and vergence drift we only analysed fixations where the measured fixation disparity fell within 2.5 standard deviations of the mean for each participant in each condition (<1% of fixations). Thus, we were able to exclude any atypically large fixation disparities (e.g., bigger than 2 deg), which may have occurred as a result of tracker error. At the same time, basing the exclusion criteria around the performance of each participant in each condition, we retained the typically larger fixation disparities observed in monocular reading due to increased divergence of the occluded eye.

We computed Linear Mixed-effect Models (LMMs) using the *lmer* function from package lme4 (version 1.1-11, Bates, Maechler, Bolker, & Walker, 2014) in R, an open-source programming language and environment for statistical computation (R Development Core Team, 2012). We used the lmerTest package to compute *p*-values (Kuznetsova, Brockhoff, & Christensen, 2016). Values for first fixation duration and gaze duration were log-transformed prior to running the models, due to the skewed right tails of their distributions. We report regression coefficients (*b*s), which estimate the effect size relative to the intercept, as well as standard errors (*SE*s) and *t*-values. Given the number of participants and observations per participant, the *t*-distribution will approximate the *z*-distribution; therefore we consider as statistically significant those cases where $|t| > 1.96$ (Baayen, Davidson & Bates, 2008). For binary dependent variables such as regression probability we used generalised linear mixed models (*glmer* function from package lme4) and report the Wald *z* and its associated *p*-value.

4.3 Results

4.3.1 The spatial extent of the binocular advantage in parafoveal preview

First, we consider results that are relevant to our first objective: to determine the spatial extent of binocular input to the right of fixation that is needed in order for reading behaviour to reach asymptote. We examine both global reading performance across the entire sentences, as well as local measures of word processing.

Table 9. Means and standard deviations for fixation durations and sentence reading time across conditions (in milliseconds).

	Condition				
Measure	Binocular	2-word window	1-word window	1-char window	Monocular
First Fixation Duration	250.43	244.12	243.50	262.86	267.68
(SD)	*77.06*	*77.41*	*70.24*	*76.84*	*81.90*
Gaze Duration	296.41	295.43	304.46	311.73	323.23
(SD)	*129.66*	*139.15*	*143.88*	*147.15*	*145.78*
Sentence Reading Time	2476.20	2386.46	2332.13	2595.89	2617.21
(SD)	*696.08*	*669.70*	*637.90*	*636.36*	*698.36*

4.3.1.1 Global analyses

Response accuracy to the comprehension questions was uniformly high (M = 97%, range = 89% - 100 %). Descriptive statistics for all fixation time measures are presented in Table 9[4]. As expected, we found sentence reading times were longer in the full monocular control condition than the full binocular control condition ($b = 225.67$, $SE = 75.16$, $t = 3.01$, $p = .008$). This is in line with previous findings (Jainta et al., 2014, 2016; Jainta & Jaschinski, 2012; Nikolova et al., 2016),

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[4] All LME models for the eye movement measures reported in Table 9 had the following structure: *Model <- lmer(DV ~ Condition + (1+Condition|Participant) + (1|Item), data = dataset).*

suggesting that reading is most efficient when binocular input is available throughout the sentence and least efficient during monocular presentation. Importantly, however, sentence reading times were not significantly longer than those in the full binocular control condition either when word *N+1* was binocular (*b* = -75.72, SE = 56.06, *t* = -1.35, *p* = .19), or when both word *N+1* and word *N+2* were binocular (*b* = -105.55, *SE* = 63.52, *t* = -1.66, *p* = .12). The critical difference was observed when parafoveal binocular input was only available for the first character of word *N+1*. In that condition, sentence reading times were significantly longer than in the full binocular control condition (*b* = 138.13, *SE* = 60.57, *t* = 2.28, *p* = .03). In other words, participants were slower to read sentences where parafoveal binocular input was restricted to the first character of word *N+1*, but reading times were similar to the binocular control condition when the whole of word *N+1* was binocular (see *Figure 8).*

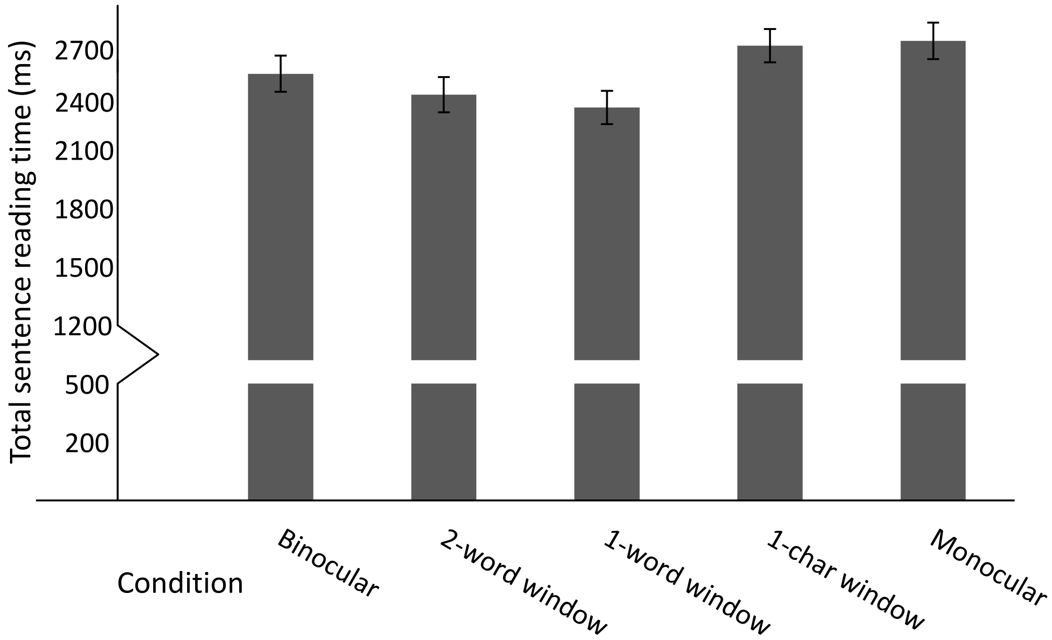

Figure 8. Mean total sentence reading time in the five different presentation conditions (the bars represent standard error).

We also investigated regression probability and number of fixations made per sentence. We observed no significant differences in regression probability between the full binocular and monocular control conditions (*b* = 0.13, *SE* = 0.09, *z* = 1.29, *p* = .13), or between the full binocular control condition and the three moving window conditions (*b*s < 0.05, *p*s > .32). Similarly, with the number of fixations made per sentence, we found no differences across conditions (all *t*s < 1). It seems, therefore, that although cognitive processing of the text was slower when parafoveal preview was monocular, this did not cause the reader to alter their overall pattern of inspection of the text.

4.3.1.2 Local analyses

Next, we considered two local measures of word processing: first fixation duration (FFD; the duration of the initial, first-pass fixation on a word) and gaze duration (GD; the sum of first-pass fixations on the word before the eyes move onto another word in the sentence). We did not have a target word in each sentence; rather, these local measures were calculated for each word in the sentence. We wished to examine in more detail the locus of the effect of monocular parafoveal preview on overall sentence reading times, given that monocular preview did not affect the overall pattern of inspection, to determine whether this did indeed result from reduced efficiency of word processing.

We found that FFDs were inflated in the full monocular condition relative to the full binocular condition (*b* = 0.08, *SE* = 0.02, *t* = 5.36, *p* < .001), and were also longer in the one-character window condition (*b* = 0.05, *SE* = 0.01, *t* = 3.85, *p* < .001). There was no significant difference in FFD between binocular reading and the other two moving window conditions (one-word window *N+1*: *b* = -0.02, *SE* = 0.01, *t* = -1.46, *p* = .12; two-words window: *b* = -0.02, *SE* = 0.02, *t* = -1.29, *p* = .13). Once again, the latter two conditions were not significantly different from each other, indicating no additional benefit of binocular input for word *N+2*, as well as word *N+1*.; thus, FFD in the one-word window condition was not significantly different from FFD in the binocular control condition.

For GD, the pattern of results was similar to that for FFD. GDs in the full monocular condition were about 35 ms longer than those in the full binocular condition (*b* = 0.07, *SE* = 0.02, *t* = 3.58, *p* < .01). In addition, there was a marginally significant 16ms increase in GD in the one-character window condition relative to the full binocular baseline (*b* = 0.04, *SE* = 0.02, *t* = 1.92, *p* = .07). Again, there were no significant differences in GD between the one-word window and two-word window conditions and the binocular baseline (*t*s < 1).

4.3.2 The locus of the binocular advantage in parafoveal preview

Recall that our second objective was to determine whether disruptions to reading from monocular parafoveal input could be attributed to targeting of binocular saccades towards a monocular parafoveal input, or to a disruption of word identification processes for parafoveal text. The analyses reported in Section 3.1 clearly demonstrated that insufficient binocular parafoveal preview was available then disruption to word-level processing occurred, as indexed by reading time measures. It remains possible, however, that saccadic targeting might also be disrupted by monocular parafoveal preview.

	Condition				
Measure	Binocular	2-word window	1-word window	1-char window	Monocular
Saccade duration	45.90 *(8.21)*	45.10 *(9.00)*	45.17 *(8.94)*	44.56 *(7.84)*	46.78 *(9.42)*
Saccade amplitude(R)	1.57 *(0.65)*	1.58 *(0.66)*	1.55 *(0.62)*	1.53 *(0.61)*	1.62 *(0.68)*
Saccade amplitude (L)	1.51 *(0.63)*	1.52 *(0.65)*	1.50 *(0.65)*	1.46 *(0.60)*	1.56 *(0.67)*
Peak velocity (R)	324.68 *(117.67)*	332.23 *(117.02)*	328.10 *(120.30)*	328.17 *(117.52)*	329.73 *(119.20)*
Peak velocity (L)	236.27 *(81.10)*	238.01 *(83.22)*	236.44 *(81.61)*	243.31 *(80.94)*	244.56 *(85.29)*
Landing position (R)	2.47 *(1.34)*	2.51 *(1.40)*	2.41 *(1.34)*	2.42 *(1.32)*	2.40 *(1.35)*
Landing position (L)	2.19 *(1.31)*	2.38 *(1.37)*	2.35 *(1.36)*	2.31 *(1.32)*	2.25 *(1.37)*

Table 10. Mean values and standard deviations for saccade duration (ms), saccade amplitude (deg), peak velocity (deg/sec) and saccade landing position (characters).

4.3.2.1 Binocular saccadic programming

For the next part of the analysis, we only considered progressive saccades. Observed descriptive values for saccade landing positions, amplitudes, durations, and peak velocities can be found in Table 10. Firstly, we measured the accuracy of saccades by analysing the landing position of each eye separately as a function of presentation condition, target word length and launch site distance. Mean landing positions are plotted in *Figure 9*. On average, the right eye tended to land less than half a character space (0.11 deg) further to the right than the left eye (b = 0.35, *SE* = .11, t = 3.12, p < .001). We did not, however, find this pattern to be different across presentation conditions. In other words, there was no significant influence of presentation condition on the relative landing positions of the two eyes (all *p*s > .18). In fact, the most reliable predictors of saccadic landing positions were target word length (b = -0.16, *SE* = .02, t = 8.79, p < .001) and launch site distance (*b* = -1.37, *SE* = 0.50, *t* = 2.77, *p* = .006)[5]. These results suggest that participants tended to target a position about 0.04 deg further to the left of the centre of a word if it was long, and about 0.34 deg further to the left of the word centre if the launch site was more distant.

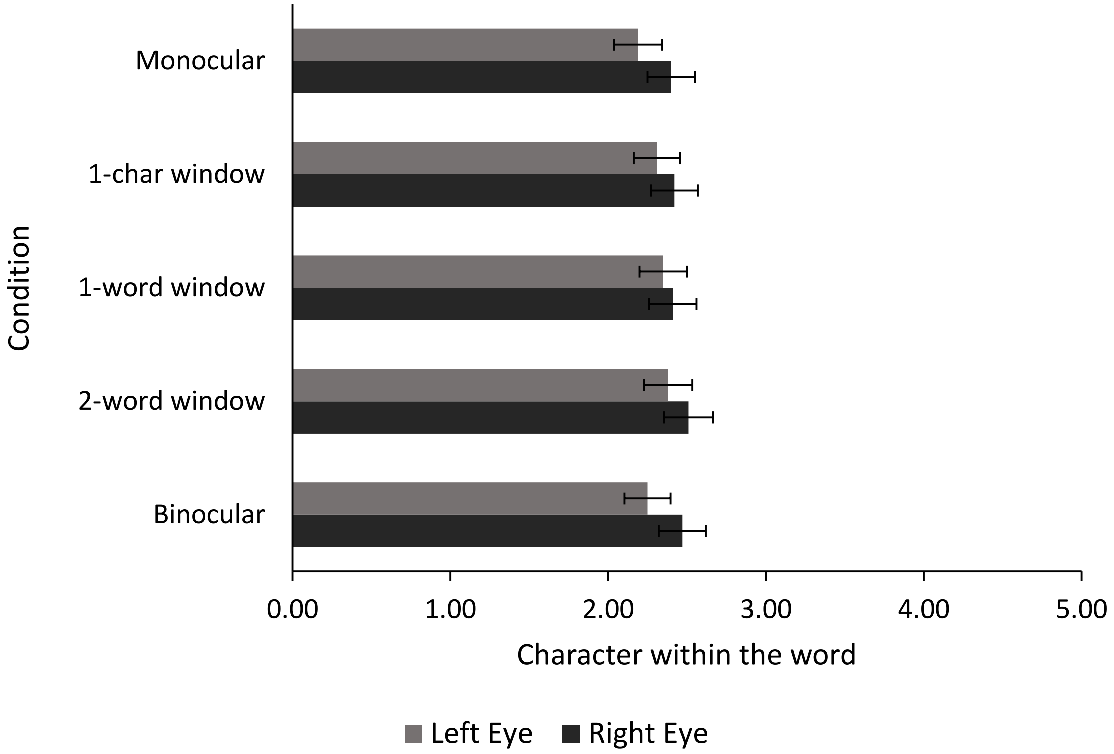

Figure 9. Mean landing positions of the left and right eye in all presentation conditions (in characters). The value of 0 represents the blank space before the word.

Next, we analysed saccade amplitude (reported in degrees of visual angle), duration (reported in ms), and peak velocity (reported in deg/sec). We found that the right eye's saccade amplitude exceeded the left eye's saccade amplitude, and the difference was statistically reliable (*b* = 0.04, *SE* = 0.02, *t* = 2.17, *p* = .01). Additionally, we observed a small effect of condition on overall saccade length and duration. In the one-character window condition, saccade amplitude for both eyes was slightly reduced (*b* = -0.07, *SE* = 0.03, *t* = -2.10, *p* = .04) and saccades were marginally shorter in duration (*b* = -1.23, *SE* = 0.63, *t* = -1.95, *p* = .07) relative to the full binocular control condition. In the one-word window condition, saccade amplitude was reduced (*b* = -0.06,

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[5] The final LME model for saccade landing position had the following structure: *Model <- lmer(DV ~ Eye + Condition + Target_Word_Length + Launch_Site + (Condition+Launch_Site|Participant) + (Target_Word_Length + Launch_Site|Item), data = dataset).*

SE = 0.03, *t* = -2.63, *p* = .01), but there were no significant differences in duration (*t* < 1) relative to the full binocular condition. No other presentation conditions influenced either saccade duration or saccade length (all *t*s < 1). Critically, we did not find any interactions between eye (left vs. right) and condition in any of the reported analyses on saccade amplitude. Thus, manipulation of monocular parafoveal preview did not influence the binocular coordination of saccades in terms of either amplitude or duration.

Finally, we analysed saccade peak velocity. This was computed by taking the derivative of the position response recorded by the eye trackers using a Savitzky-Golay 2-point central difference algorithm with the *savitzkyGolay* function from the prospectr package in R (Stevens & Ramirez-Lopez, 2014). The peak velocity of the left-eye and right-eye saccades were quantified as the maximum value within each movement. We computed a linear mixed-effect model with the peak velocity of all forward saccades as a dependent variable and tracked eye (left or right) and presentation condition as fixed effects. We found that, across all presentation conditions, the right eye's peak velocity was approximately 89 deg/sec higher than the left eye's peak velocity (*b* = 88.78, *SE* = 1.48, *t* = 59.97, *p* < .001). Once again, this effect did not vary as a function of condition, suggesting that the amount of binocular input available in the parafovea did not influence the programming of saccades. Instead, regardless of presentation condition, in all forward saccades the abducting eye (right) made faster movements than the adducting eye (left).

4.4 Discussion

In the present experiment, we investigated the extent to which parafoveal pre-processing requires a binocular visual input in order to operate efficiently. Below we discuss our findings with relation to our two key objectives: 1) to determine the spatial extent of parafoveal binocular input that is needed for reading behaviours to reach asymptote; and 2) to determine whether binocular parafoveal advantages can be attributed to enhanced saccadic targeting processes, a facilitation in the efficient extraction of information from upcoming text for the purposes of word recognition, or both. Our results demonstrated that while our experimental manipulation clearly influenced reading time measures, reflecting a reduced efficiency in word processing, there was no such influence on measures of binocular saccadic programming. We now discuss these results in relation to both our objectives. In terms of the spatial extent of parafoveal binocular input that is necessary for fluent reading, our results indicated that reading performance reached asymptote when word *N+1* was entirely binocular in the parafovea. In fact, we found that no benefit to processing speed was obtained by presenting just the first character of word *N+1* binocularly.

These results have clear relevance for understanding the perceptual span during binocular and monocular reading. Previous research has shown that the perceptual span in English extends from about the beginning of the currently fixated word to about two words to the right of fixation. For example, Rayner et al. (2009) found that for skilled young adult readers, if only one word to the right of word *N* was available in a moving-window paradigm then reading speed was reduced, but if two words (word *N+1* and word *N+2*) were available then reading speed did not differ from that observed in the no-window condition. That is, readers benefitted from having about three words available during each fixation: the fixated word and two words to the right, for reading in English. We have now shown that, with respect to binocular visual input, only one word to the right of fixation needs to be presented to both eyes in order for reading to proceed uninterrupted. The fact that no additional benefit was obtained from a binocular preview of word *N+2* is likely an indication that the region within the perceptual span for which binocular visual input is crucial includes word *N* and word *N+1*. In addition, our findings indicate that the first character of a word, while particularly important for lexical identification during both direct fixation and parafoveal pre-processing (Pagan et al., 2015; White et al., 2008), may not be sufficient to allow for binocular advantages to be obtained from parafoveal text.

As mentioned previously, our results indicated that it was word processing, rather than binocular saccadic targeting, which suffered when the spatial extent of parafoveal binocular input was reduced. To understand this effect, it is important to consider the widely accepted finding that, during normal reading, gaze location and attention do not always coincide. Previous work has shown that orthographic processing of words can begin prior to those words being directly fixated (Balota, Pollatsek & Rayner, 1985; Binder, Pollatsek & Rayner, 1999). In fact, according to Miellet and Sparrow (2004), parafoveal preview benefit can (at least to some extent) be attributed to partial activation of the target word's lexical entry prior to direct fixation. The degree of activation depends on the degree of similarity between preview and target. For instance, a visually identical preview can be expected to elicit maximal orthographic and phonological activation of the target word's lexical entry prior to direct fixation. In the current study, all previews were identical to the actual words in in terms of the content of the printed stimulus: we had no letter substitutions or letter masking. The only difference between a word and its parafoveal preview was whether all characters of the preview were binocular in the parafovea prior to direct fixation. Our results clearly indicated that a binocular advantage was only obtained from binocular preview of the whole of word *N+1*. Our findings suggest, therefore, that a monocular parafoveal preview is not sufficient to activate the target's lexical entry and facilitate processing upon direct fixation.

Existing evidence indicates that the binocular advantage to parafoveal pre-processing of words cannot be explained entirely by changes in the visual quality of the preview. Previous work has demonstrated that a reduction in contrast using the binocular contrast summation ratio of 1.4 (Campbell & Green, 1965) does not influence reading performance or the speed of lexical access in the same way that switching from binocular to monocular presentation does. Further investigation of the binocular summation ratio for lexical stimuli is required in order to fully understand the role of contrast and luminescence for binocular advantages in reading. Existing evidence shows that more drastic visual degradation manipulations that can influence the ability to obtain a preview benefit (e.g. spatial frequency manipulations, Patterson, McGowan, & Jordan, 2014; contrast reduction manipulations below 40%, Jainta et al., 2016; Sheridan & Reingold, 2013). However, such dramatic changes in visual quality do not occur for individuals with normal binocular vision when switching from binocular to monocular presentation. Another potential explanation for the observed effects may be, therefore, that monocular parafoveal text poses a challenge for word identification processes prior to direct fixation by making the extraction of useful information from the perceptual span less efficient than during binocular reading.

This explanation is also supported by our analysis of saccadic parameters across conditions, which showed little influence of presentation condition on binocular characteristics of saccade amplitude, landing position, duration or peak velocity. That is, participants were able to target the PVL (slightly to the left of the word centre) in all presentation conditions. In fact, the most significant sources of influence on saccadic landing position were launch site distance and target word length, these effects being well-established within the literature (McConkie, Kerr, Reddix, & Zola, 1988; Rayner, 1979). Furthermore, we replicated previous findings of muscle imbalance and transient divergence during binocular saccades in adults with normal vision, as reported by Collewijn, Erkelens, and Steinman (1988), Vernet and Kapoula (2009) and Yang and Kapoula (2003). Critically, however, our findings indicate that denying binocular visual input for the word to the right of fixation does not affect the physiological mechanisms responsible for maintaining typical binocular coordination. Instead, parafoveal monocular input appears to exert its influence on reading times by disrupting readers' ability to extract the information necessary for facilitating efficient word identification.

Similar results were reported by Rayner et al. (2006) who found, in their disappearing text experiment, that participants targeted the PVL both when word *N+1* disappeared 60 ms after fixation onset on word *N*, and when it was masked with Xs. In the case of disappearing text, when word *N+1* had either no preview (disappearing condition) or an invalid preview (X mask), participants were still able to use visual information about the width of the blank space/mask and the surrounding word in order to target their saccades appropriately. They did not, however, have the opportunity to extract any linguistic cues from parafoveal preview that would have allowed for pre-processing of the word’s cognitive representation, which resulted in an overall disruption to reading. In the present experiment, we showed that information about word *N+1* must be available to both eyes simultaneously in order for efficient word identification to take place.

In conclusion, we report a gaze-contingent dichoptic moving window experiment in which the spatial extent of parafoveal binocular information available to readers was varied on a fixation-by-fixation basis. We observed parafoveal binocular advantages when word *N+1* was entirely binocular, but all other text to the right of fixation was monocular. The disruption caused by presenting parafoveal text monocularly could not be counteracted if only the first character of word *N+1* was binocular, and no additional benefit in performance was observed when both word *N+1* and word *N+2* were binocular. Critically, we found these effects on fixation times but not on saccadic parameters. We conclude, therefore, that while a monocular visual presentation does not disrupt the ability to use parafoveal visual input for accurate saccadic targeting, it can prevent readers from efficiently extracting sufficient information during pre-processing to facilitate word recognition during subsequent direct fixation.

Chapter 5: General Discussion

5.1 Summary

The motivation for this thesis was to study the role of binocularity – a fundamental characteristic of human visual function – and its relationship with the complex psychological process of reading. A large number of studies have been dedicated to the exploration of binocular vision, its underlying physiological and neural mechanisms, its role in depth perception and stereopsis, and its pathology and treatment (Howard & Rogers, 2005; Steinmann et al., 2002). Similarly, a vast and detailed literature has been devoted to the empirical investigation of oculomotor control during reading and the cognitive processes associated with written language comprehension (Rayner, 1998, 2009; Schotter et al., 2014). There are, however, surprisingly few examples of common research focus between the two fields. That is, only a small number of studies have considered the role of binocular vision in relation to written text processing. Thus, the mechanisms via which binocularity influences the decisions of when and where to move the eyes in reading have remained largely unspecified.

The aim of this thesis was to address limitations in our current theoretical understanding of the role of binocular vision with relation to language processing during reading. It considered the three-way relationship between binocular vision, oculomotor control and the cognitive processing associated with written language comprehension. The review of the literature presented in Chapter 1 described the current understanding of this relationship and limitations in our existing knowledge about the role of binocular vision in reading. Following that, three empirical chapters were dedicated to exploring this three-way relationship in the context of both single-word identification and natural sentence reading. Chapter 2 considered the role of vertical motor and sensory fusion during word identification, alongside the cognitive processes associated with lexical access. Chapter 3 focused on binocular advantages in reading, and whether they could be explained by facilitation of foveal or parafoveal text processing. Chapter 4 quantified the amount of parafoveal binocular input necessary for fluent reading, and explained how this input informs processing of parafoveal text prior to direct fixation.

The present chapter will provide a summary of the reported empirical findings, as well as a discussion of their implications for the developing understanding of binocular visual processes in the context of word identification and oculomotor control during reading. Finally, the chapter will consider the broader theoretical implications relating to our evolving understanding of the role that binocular vision plays in the context of reading, as well as an overview of outstanding issues and suggestions for future research.

5.2 Chapter 2: Vertical vergence movements during word identification

Binocular coordination is critical to successfully attaining a fused, stable representation of the visual environment, which in turn is essential for performing a variety of tasks, including reading. In Chapter 2, the process of binocular fusion during word identification was explored by considering the influence of vertical disparity induced in lexical stimuli. The objectives of the experiment were 1) to measure vertical vergence responses to vertical disparity in the parafovea and upon fixation; 2) to establish the tolerance of the vergence system for vertical disparity in lexical stimuli; 3) to investigate the interaction between binocular image disparity and word identification processes for high-frequency and low-frequency words.

5.2.1 Summary and Implications

In some respects, the findings from Chapter 2 were initially surprising. One of two results was expected: either the vertical disparity manipulation would result in visual disruptions and diplopia, or it would elicit vertical vergence movements, similar to horizontal disparity in order for the disparate images on the screen to be fused. The findings revealed, however, that when participants made a saccade onto a centrally presented stimulus with induced vertical disparity, they did not make corresponding disparity-reducing vertical vergence movements. Vergence adjustments were not observed during the saccade, or during the fixation on the word itself, suggesting that participants were not sensitive to vertical disparity in the parafovea. Nevertheless, the perception of participants was always one of a fused stimulus, even when vertical disparity was approximately equal to half the height of a character space. Indeed, as can be seen from the figures presented in Chapter 2, the disparity manipulation was obvious when participants viewed the screen without shutter goggles. The findings were in direct contrast to the vergence responses to words presented with a horizontal disparity observed by Blythe at al. (2010), where corresponding vergence movements were made immediately upon fixation to compensate for the induced image disparity. With respect to the ability to process words presented with induced vertical disparity, no delay of processing across conditions was found and a significant frequency effect was observed when disparity was present in the stimuli, as well as when it was absent.

The results presented in Chapter 2 have direct implications for understanding the behaviour of the binocular vergence system during both fixations and saccades in the process of identifying written words. While fixational vergence movements have been studied in non-reading tasks, it is important to consider them in the context of written word identification, not simply because of the significant differences in visual complexity and spatial frequency profile that exist between the lexical stimuli used in the present experiment and the random-dot stereograms or nonius stimuli typically employed in psychophysical studies (Howard & Rogers, 2012). Comprehending written text is not only a matter of encoding its intricate visual form, but also of engaging in cognitive processing associated with accessing the lexical representation of that visual form. Word identification is at the forefront of a series of linguistic operations whose ultimate goal is to derive a mental representation of meaning from an abstract written form.

In that sense, the findings presented in Chapter 2 speak to the relationship between the functional characteristics of the binocular visual system and the process of written word identification. Human vision evolved in response to the fundamental aspects of the visual environment. Our eyes are horizontally separated and vertically aligned, because our environment is such that binocular cues to depth exist in a horizontal, rather than the vertical dimension. The visual system can therefore rapidly and accurately create a perception of depth based on the horizontal displacement of two-dimensional retinal projections relative to each other. In a hypothetical scenario wherein the vertical displacement of retinal projections were informative with relation to depth, the human visual system might well have evolved accordingly – with vertically separated, horizontally aligned eyes.

The critical point, however, is that this physical configuration of the visual system underlies the pattern of fixation disparity and vergence movements that was observed in Chapter 2 during written word identification – a task that did not require depth discrimination. Horizontal vergence movements occurred readily, without horizontal disparity in the stimuli themselves. Vertical vergence movements – even during a task specifically designed to elicit them – were limited. The two vergence systems – horizontal and vertical – were clearly dissociated, and the dissociation was likely a result of their respective function. While horizontal vergence is necessary to attain a detailed perception of depth from the visual environment, vertical vergence subserves the continual maintenance of a single, unified percept over which horizontal vergence can operate for fine-tuned depth computations. It might be the case that inducing both horizontal and vertical disparity within the same stimulus during word identification would disrupt the ability to obtain a single, fused percept, because of the increased demand for both global vertical alignment and fine-tuned horizontal disparity computations simultaneously.

The second important implication with respect to Chapter 2 is that while the behaviour of the vergence system during fixations differed from what was previously reported for horizontal disparity (e.g., Blythe et al., 2010), it behaved comparably during saccades. That is, the pattern of landing positions analysed in Chapter 2 revealed that readers were not sensitive to vertical disparity in the parafovea and made no corresponding vertical vergence adjustments during saccades. Similar findings were reported by Blythe at al. (2010), where participants targeted parafoveal words with induced horizontal disparity on the basis of the length of the combined (not fused) stimulus. For example, if a 6-letter word was presented with 2 characters of horizontal disparity, resulting in an 8-character non-fused stimulus, participants targeted their saccades towards the preferred viewing location for an 8-letter word. That is, participants perceived both dichoptic images in the parafovea and targeted their saccades on the basis of a combined (but not fused) input. Comparable findings were also reported in a non-reading task by Blythe, Holliman, Jainta, Tbaily, & Liversedge (2012), where participants made appropriate vergence adjustments during saccades when moving their eyes between real LEDs in depth, but no such adjustments were made when saccading between similar targets presented stereoscopically on a display.

Overall, these comparable findings speak to differences in oculomotor behaviour between real-word viewing and stimuli presented on a flat surface (e.g., standard computer display). During real-world viewing, individuals are able to make vergence adjustments during both saccades and fixations to compensate for the depth cues available in the parafovea (Blythe at al., 2012; Sprague, Cooper, Tošić, & Banks, 2015). This is not the case when viewing text (or other dichoptically presented stimuli) on a monitor. Under such viewing conditions, vergence adjustments are only made during direct fixation on the target. That is, the visual system is not sensitive to binocular disparity cues in the parafovea when processing images on a two-dimensional surface. What these findings imply is that while the horizontal and vertical vergence system are dissociated with relation to their function in maintaining binocular fusion, they are tightly linked in the context of binocular saccadic targeting. This is further evidence that the two systems, functionally distinct, underlie the same fundamental process – maintaining a single, fused binocular percept across eye movements.

In conclusion, Chapter 2 demonstrated that during lexical identification, the visual system responds differently to induced vertical disparity in the stimuli than it does to induced horizontal disparity. The reported findings suggest that this dissociation in vergence responses during fixations is related to the functional distinction between the horizontal and vertical vergence system with relation to maintaining a fused percept during foveal processing when identifying written words. While the two systems have distinct roles, they are tightly linked, and operate comparably during saccades to disparate parafoveal stimuli, suggesting a common parafoveal target selection mechanism. Ultimately, the experiment presented in Chapter 2 provided evidence that the fundamental physical make-up of the binocular visual system is functionally relevant to the attainment of a fused binocular percept during the processing of lexical stimuli.

Further work is needed to investigate the response of the visual system to induced disparities in all directions during lexical processing in order to quantify the degree of interdependence between horizontal and vertical fusion mechanisms.

5.3 Chapter 3: Foveal and parafoveal binocular advantages during sentence reading

Recent findings indicated that reading comes with a binocular advantage: reading times are typically shorter and word identification processes operate more efficiently when text is presented binocularly, rather than monocularly (Jainta & Jaschinski, 2012; Jainta et al., 2014). These findings further indicate that binocular vision is involved in oculomotor control in reading and influenced the decision of *when* and *where* the eyes move when a piece of text is being processed. The experiment presented in Chapter 3 expanded the existing understanding of binocular advantages in reading by investigating whether they could be attributed to more efficient encoding of foveal information, or more effective pre-processing of parafoveal information in binocular relative to monocular presentation conditions. Additionally, the findings provided insight into the underlying mechanisms that govern the distinct relationship between binocular vision, oculomotor control and cognitive processing associated with foveal and parafoveal influences on word identification.

5.3.1 Summary and Implications

In order to answer the theoretical questions posed in Chapter 3, it was necessary to develop an experimental technique which allowed for binocular visual input to be made available on a moment-to-moment, gaze-contingent basis. Unlike Jainta et al. (2014), who presented sentences with a single display change prior to a target word, the dichoptic moving-window presentation technique described in Chapter 3 ensured that a display change occurred prior to each fixation on a new word within the sentence. This manipulation allowed for the specific influence of binocular vision for foveal and parafoveal processing to be considered both with relation to sentence-level measures of reading performance and with relation to word identification for a target manipulated for lexical frequency.

Four key sets of findings were reported with respect to binocular vision and its role in reading. Firstly, a disruption to reading was expected to occur when the fixated word was monocular, but all other text was binocular. Based on Jainta el al.'s (2014) results, it was also expected that monocular presentation for the fixated word would slow down foveal processing, thus resulting in longer fixation times and increased sentence reading times. Instead, the results indicated that participants were able to read without disruption in that condition: there was no cost to sentence processing times, and our analyses of the number of fixations and regressions further demonstrated that no particular difficulty was experienced by readers. In other words, even if the fixated word was monocular on each fixation, participants were still able to obtain a binocular advantage from the binocular preview of that word. This likely facilitated word processing, thus resulting in a smaller cost to reading performance. This finding underlines the necessity of effective parafoveal processing of words prior to direct fixation for efficient reading.

Secondly, when text to the left of fixation was monocular, it was predicted that some disruption to reading might occur. This prediction was based on findings by Jordan, McGowan, Kurtev and Paterson (2015) showing that the perceptual span in English may extend further to the left than previously thought, in many cases beyond the traditionally assumed boundary of the beginning of the fixated word (McConkie & Rayner, 1975, 1976; Rayner, Well, & Pollatsek, 1980; Underwood & McConkie, 1985). That was not, however, what was found with respect to binocular advantages – there was no disruption to reading performance when text to the left of fixation was monocular. Thirdly, presenting monocular text to the right of fixation was also expected to cause disruption to reading. That was precisely what was found: in that condition, participants' reading speed was significantly reduced and they experienced considerable disruption to fluent reading. In other words, the results suggested that when each word in a sentence was previewed binocularly but fixated monocularly, reading proceeded efficiently, relative to when larger portions of the sentence to the right of fixation were presented monocularly. It is important to point out that in this condition, even though words were fixated binocularly, readers were not able to obtain a binocular advantage, likely due to the disruption of parafoveal pre-processing when text to the right of fixation was monocular.

Finally, the investigation of binocular coordination measures indicated that no increase of fixation disparity was present when text to the right of fixation was monocular (but the fixated word was binocular), despite the considerable increase in processing times. Thus, the findings presented in Chapter 3 provide evidence that uninterrupted binocular visual input plays a key part in the efficient pre-processing of information to the right of fixation, and the observed disruption to reading when no binocular input is available for that text is not related to a disruption in binocular coordination.

Overall, the experiment in Chapter 3 demonstrated a strong association between binocular vision and the efficient pre-processing of parafoveal text to the right of fixation. It is important to note that reading performance only suffered when binocular visual input was denied in the direction of reading. This finding is in line with previous studies (Liversedge et al., 2004;

Rayner et al., 2003, 2006; Rayner et al., 2013), which have demonstrated that the critical region from which readers obtain information during reading of English and other languages read from left to right is to the right of fixation. To be clear, these results do not imply that there is a functional difference between binocular fusion processes in the right and left visual field. They suggest, instead, that because in English more attention is allocated to text to the right of fixation than to the left, and because processing demands associated with that text guide eye movements, the need for a high-quality unified binocular input is more pronounced in the pre-processing of that text prior to direct fixation.

A reasonable explanation for the observed effects might have been that denying monocular visual input for a large portion of the text to the left or to the right of fixation could have influenced binocular coordination. Such a manipulation effectively reduces the available input for successful binocular fusion, which might cause difficulty in attaining a single, unified percept of the text, thus requiring additional time for disparity-reducing vergence movements to be made. This, however, was not found to be the case. In fact, binocular coordination remained efficient in all three gaze-contingent conditions reported in the experiment, and was only impacted when the entire sentence was presented monocularly. These results imply that there is dissociation between binocular coordination processes and reading performance when text to the right of fixation is monocular. They also suggest that the disruption to reading observed in this condition cannot be attributed to disruptions in oculomotor processes associated with maintaining a single, unified percept of the text.

Instead, the disruption to reading that was observed in the parafoveal monocular condition could be attributed to a reduction in processing efficiency resulting from the absence of binocular visual input to the right of fixation. A similar mechanism has already been proposed to explain the reduction of the frequency effect observed by Jainta et al. (2014, 2017), who found that when a high-frequency target word was previewed and fixated monocularly, it could no longer be processed faster than a low-frequency word under the same presentation conditions. The absence of binocular visual input – and, by definition, the absence of a fused binocular percept – appeared to influence the efficiency with which the language processing system could identify familiar stimuli. This effect was also shown to occur separately from reductions in visual quality (specifically, contrast) that might accompany the transition from binocular to monocular viewing (Jainta et al., 2017). In other words, with respect to foveal processing, the binocular advantage for reading could be the result of optimal processing efficiency for linguistic stimuli. While at this stage, the underlying neural mechanisms of this effect are not clearly specified, it may be the case that a visual presentation that disrupts binocular fusion precludes optimal neural activation within the visual system, which in turn impacts upon the efficiency of word identification.

Similarly, the experiment presented in Chapter 3 demonstrated that when a fused binocular percept was not available for parafoveal pre-processing, reading performance suffered. It is likely, based on the reported findings, that the monocular text presented in the parafovea could not be pre-processed with an optimal degree of efficiency, which in turn prevented readers from making full use of that text in order to facilitate foveal word identification. It may be the case that a similar underlying mechanism is at play both for foveal word identification and for parafoveal pre-processing of binocular text. In other words, a fused binocular percept may be necessary to allow readers to efficiently extract useful information within the perceptual span and facilitate word recognition during direct fixation.

To summarise, Chapter 3 implemented a novel dichoptic gaze-contingent moving window paradigm to investigate the three-way relationship between binocular vision, oculomotor processes associated with binocuolar coordination and eye movement guidance. The presented experiment replicated previous findings of binocular advantages in reading, and demonstrated that, while binocular vision is important for the encoding of foveal information during reading, it plays a critical part in the efficient pre-processing of information to the right of fixation. Future work would need to explore whether this effect is present in different orthographies, and whether it is associated with saccadic targeting processes, or with the efficiency with which words are identified in the parafovea, prior to direct fixation.

5.4 Chapter 4: Binocular Advantages for Parafoveal Processing in Reading

The advantages of binocular vision for reading have been reported in several experiments, and have been shown to extend to both foveal and parafoveal processing. Chapter 3 considered a potential mechanisms for binocular advantages related to the degree of efficiency with which the word identification system operates when processing fused binocular visual input, as opposed to monocular visual input. The study reported in Chapter 4 pursued this further by considering an alternative possibility: that binocular advantages for parafoveal pre-processing might arise as a result of visual processes associated with efficient binocular saccadic programming.

5.4.1 Summary and Implications

Similar to previous research (Jainta et al., 2014, 2017), and to the findings reported in Chapter 3, the experiment reported in Chapter 4 clearly demonstrated that when readers were not provided with sufficient binocular parafoveal input, their reading performance suffered. In addition, the findings quantified how much parafoveal binocular input can be considered sufficient for fluent reading. While readers were expected to be able to obtain parafoveal preview benefit if only the first character of word *N+1* was binocular, the results reported in Chapter 4 showed instead that reading performance improved only when word *N+1* was entirely binocular in the parafovea. In fact, no benefit to processing speed was obtained when the first character of word *N+1* was presented binocularly. Another important finding from the present experiment was that a two-word parafoveal binocular moving window did not yield any additional benefit over a one-word binocular window.

The findings reported in Chapter 4 have two key implications for understanding how binocular vision is related to oculomotor and cognitive processes underlying reading. Firstly, one of the main objectives of the experiment was to determine whether the binocular advantage for parafoveal processing can be attributed to enhanced saccadic targeting processes, a facilitation in the efficient extraction of information from upcoming text for the purposes of word recognition, or both. The findings clearly indicated that reduction of parafoveal binocular input influenced fixation duration measures associated with word recognition. Furthermore, the thorough analysis of saccadic parameters across conditions showed little influence of presentation condition on saccade length, landing position, duration or peak velocity. That is, participants were able to target the preferred viewing location (PVL, slightly to the left of the word centre) in all presentation conditions, and visual processes associated with saccade generation and saccade accuracy were not disrupted. Thus, these findings suggest that it is cognitive processing associated with word identification that underlies the parafoveal binocular advantage in reading.

This conclusion is in accord with the findings reported in Chapter 3 and relates to the importance of uninterrupted parafoveal processing for fluent reading. The identification of a word can begin prior to direct fixation, as evidenced by the widely accepted finding that attention and gaze location do not necessarily coincide during written text processing (Balota, Pollatsek & Rayner, 1985; Binder, Pollatsek & Rayner, 1999). For instance, the parafoveal preview benefit effect can (at least to some extent) be attributed to partial activation of the target word’s lexical entry prior to direct fixation (Miellet & Sparrow, 2004). When binocular visual input in the parafovea is removed, the efficiency of these pre-fixational word recognition processes is disrupted. While readers are able to target their saccades accurately when the preview is monocular, they are unable to extract high-quality parafoveal visual information in order to pre-process the word’s lexical representation.

The second key implication of Chapter 4 relates to the understanding of how processing resources are distributed across the perceptual span during binocular and monocular reading. Previous research has shown that the perceptual span in English extends from about the beginning of the currently fixated word to about two words to the right of fixation. For example, Rayner et al. (2009) found that for proficient young adult readers, if only one word to the right of word *N* was available in a moving-window paradigm, reading speed was reduced, but if two words (word *N+1* and word *N+2*) were available, reading was just as fluent as in the no-window condition. That is, readers benefit from having about three words available during each fixation: the fixated word and two words to the right, for reading in English.

The work presented in Chapter 4 shows that, with respect to binocular visual input, only one single word to the right of fixation needs to be presented to both eyes in order for reading to proceed uninterrupted. The fact that no additional benefit was obtained from having word *N+2* presented to both eyes is likely an indication that the region within the perceptual span for which binocular visual input is crucial includes word *N* and word *N+1*. This finding is related to the functional importance of binocular input for efficient pre-processing of linguistic cues for word recognition purposes. During reading in English, word *N+1* is typically the saccade target, and the optimal behaviour for the language processing system would be to identify it as efficiently as possible in order to incorporate it into the developing syntactic and semantic representation of the sentence. The data from Chapter 4 have shown that these parafoveal word recognition processes require binocular visual input in order to operate efficiently. Information beyond word *N+1, in contrast,* is not typically used for word recognition purposes (Angele & Rayner, 2011; Vasilev & Angele, 2016). Binocular visual input, however, is not necessary for that information to be efficiently used for the purposes of aiding saccadic targeting. As shown in Chapter 4, participants were just as accurate at targeting their saccades when two words to the right of fixation were binocular, as when only one word was binocular. Thus, it appears that a fused binocular percept of the text is of particular importance within the region of the perceptual span from which information is instrumentally used for word recognition, and that region typically includes word *N+1*. Beyond that point (for word *N+2, N+3*, etc.), it is likely the case that, as long as the text is presented with luminescence and contrast above the detection threshold, coarse eye guidance information about word length and interword spacing can be extracted efficiently in either presentation condition.

Overall, the results reported in Chapter 4 hint at an interesting relationship between binocular vision, oculomotor control and parafoveal processing during reading. While visual processes associated with binocular coordination and binocular saccadic targeting can operate efficiently when parafoveal text is monocular, cognitive processes associated with word recognition prior to direct fixation are disrupted. An important outstanding question concerns the extent to which these findings would translate to text where there is more variability in word length. As mentioned previously, while it is overwhelmingly agreed that readers are able to extract useful features from word *N+1* for the purposes of parafoveal processing, there is inconsistency in findings regarding word *N+2* (Angele & Rayner, 2011; Vasilev & Angele, 2016). However, with respect to binocular advantages, the importance of a binocular word *N+2* might increase if word *N+1* is particularly short, as it would be more likely to be skipped (Drieghe, Rayner, & Pollatsek, 2005). In those situations, participants might require binocular input further into the parafovea in order to efficiently pre-process the word they land on after the skip. Therefore, future work would ideally compare binocular advantages for parafoveal processing while taking into account variability in word lengths and skipping rates.

5.5 What is binocular fusion and why is it important for reading?

The three experimental studies presented in this thesis were designed with a common objective: to investigate the complex three-way relationship between binocular vision, oculomotor control and cognitive processing during single-word identification and natural sentence reading. At the basis of this three-way relationship is the concept of binocular fusion. This concept may initially appear straightforward to define: it is a perceptual state of single, unified, stable vision, characterised by motor and sensory components (Howard & Rogers, 1995). The necessary prerequisites for obtaining a fused binocular percept have also been clearly defined. Worth (1921) postulated that in order for binocular fusion to occur, the two visual inputs presented to the eyes must be perceived simultaneously, must be sufficiently similar to each other in colour, brightness and size, and must be projected to corresponding retinal locations. If those conditions are not met, a fused binocular percept will not be experienced. Instead, one of three possible perceptual states will be experienced. Firstly, perception of one visual input may be temporarily inhibited (suppressed) in order to prevent confusion. Secondly, if the inputs are simultaneously perceived and are projected to corresponding retinal locations, but are not sufficiently similar, binocular rivalry may occur. That is, perception may alternate between the two visual inputs (Freeman, 2005). Finally, if the inputs are simultaneously perceived and are sufficiently similar, but their retinal locations do not correspond, diplopia (double vision) may be experienced (Liversedge et al., 2006b).

One important point, however, is that the existing definition of binocular fusion does not necessarily capture the importance of this concept in the context of reading. This is a matter that, until recently, received very little attention from researchers using eye-tracking methodology to study reading, for rather understandable reasons. In our daily lives, we typically encounter text on two-dimensional surfaces, and processing that text does not usually require stereopsis, or large eye movements in depth. In fact, as demonstrated by Rayner et al. (2003, 2006) and Liversedge et al. (2004), in order to engage in the sophisticated cognitive operations involved in recognising a word, it is only necessary to glimpse it for as little as 50-60 ms. Why is it, then, that binocular fusion in the context of reading should be the subject of thorough empirical investigation?

The human visual system evolved around two horizontally separated, vertically aligned visual receptors. As a direct consequence of that, our typical perception of written text as stable and unified is the product of a process wherein two separate visual inputs are combined into one. These fundamental physical characteristics of the visual system are evident in the way readers effortlessly cope with vertical fixation disparity during word recognition. Additionally, the empirical findings reported in the preceding chapters suggest that oculomotor control in itself does not suffer when binocular visual input is denied. Readers are able to accurately target saccades towards monocular input. In the context of computational models of eye movement control in reading, such as E-Z Reader and SWIFT, and ideal-observer models such as Mr. Chips, these findings have two potential implications. First, binocularity may influence the visual processes that take place when information from the fovea or parafovea is encoded. Previous research has considered whether changes in visual characteristics such as contrast when switching between binocular and monocular viewing affect reading performance (Jainta et al., 2017). The results showed a complex relationship between binocular vision, contrast reduction and lexical processing efficiency, which suggested that the influence of binocularity in reading could not be entirely attributed to changes in visual quality between binocular and monocular viewing.

Critically, a second possibility for incorporating binocular vision into a broader theoretical or computational framework of reading would be to consider its interaction with the cognitive processes that take place during word recognition, both for directly fixated words and for pre-processing of text in the parafovea. Consider, for example, the findings reported above which suggest that the default state of binocularity is also intricately connected with the ability of the language processing system to operate with optimal efficiency. Binocular fusion appears to allow readers to rapidly utilise their lifetime of experience with words of different lexical frequency. It also, somewhat paradoxically, allows readers to efficiently pre-process text they have yet to directly fixate. In all these cases, a fused binocular percept seems to have utility beyond providing optimal visual quality for the text, maintaining the alignment of the eyes, or ensuring accurate saccadic targeting. Instead, the concept of binocular fusion in reading appears to be closely related with the cognitive operations involved in efficient foveal word recognition and parafoveal pre-processing.

The precise nature of this relationship requires further investigation. One explanation, proposed by Jainta et al. (2017) and mentioned above, concerns differences in neural activation between binocular and monocular viewing. For example, it may be the case that when binocular fusion is not possible during reading, this could result in an additional perceptual state, aside from the three outlined by Worth (1921). In that state, while the reader remains unaware of any visual changes in the text and experiences no visual disturbances, their language processing system and their ability to obtain linguistic cues from parafoveal text and integrate them across saccades operate less efficiently, due to reduced neural activation.

Another explanation could be that the default state of binocularity of the human visual system influences the speed of retrieval of cognitive representations of words. For example, in the context of eye movement guidance during reading, the E-Z Reader model (Reichle et al., 1998; 2003; 2012) proposes that the main signal to move the eyes forward in the text is the completion of an early lexical processing stage called *familiarity check*. The familiarity-check assumption is consistent with theories of human memory which posit that recognition is driven by two components—a rapidly available sense of familiarity, followed by a slower retrieval of information. For example, in Hintzman's (1984, 1988) MINERVA 2 multiple-trace model, stimuli are encoded and represented in long-term memory as discrete memory traces, and a previously experienced stimulus can be recognised by probing memory with either the stimulus itself, or a subset of its features. According to the model, the higher the similarity between the probe and the memory trace, the higher the *echo intensity* – a scalar value which reflects the familiarity of the probe to the memory trace. This principle of familiarity may also apply to the relationship between the default state of binocularity and cognitive processing during reading. For example, it may be the case that when binocular fusion is prevented, the lexical representation of a word is less readily activated because the probe – a non-fused visual input – is less familiar than a fused one. This in turn might delay the familiarity check process, thus resulting in sub-optimal foveal or parafoveal processing.

Both the above explanations for the relationship between binocular fusion and cognitive processing during reading are, at this stage, speculative. They are, however, motivated by the empirical results presented in this thesis, as well as those reported in previous work (Jainta et al., 2014; 2017), which suggest that binocular fusion plays a role in reading beyond ensuring uninterrupted visual encoding of written text. Considering the role of binocular fusion for reading in further empirical work would be a necessary step towards clearly specifying the complex three-way relationship between binocular vision, oculomotor control and cognitive processing during written language comprehension.

5.6 Future Directions

It is important at this point to consider in more general terms the future directions for research in this area. An obvious starting point would be to address some of the limitations of the experiments presented in this thesis. Three key issues should be taken into consideration. First, while comparable to previous studies using this methodology, the number of participants in each experiment reported above was relatively small. It is important to stress that generalising from small sample sizes should be done with caution and that basing the conclusions on a larger number of observations would have been preferable. Secondly, a related issue is that the reported findings represent only the restricted sample of participants who were eligible to take part in the experiment (native English speakers with normal binocular vision and no diagnosed reading difficulties). Thus, little is known about the relationship between binocular vision and reading in a wider population of readers who do not meet these criteria. This point is discussed in more detail below and potential ways to address this limitation are explored. Finally, a crucial methodological point relates to the use of shutter goggles for dichoptic presentations, which was employed in all three experiments reported here. The shutter goggle technique does not necessarily resemble normal monocular visual perception. Recall that this technique is based on each goggle opening and closing in sequence every 8.33 ms. However, in a monocular presentation condition, while one goggle is open and the other is closed, the occluded eye still receives visual input (i.e., of a blank screen, rather than of the text presented to the other eye). This means that the shutter goggle situation is not entirely the same as, for instance, reading with one eye closed or occluded with an eye patch, where no useful visual input would be received. This is an important consideration when assessing the ecological validity of the findings from monocular presentation conditions. While those findings have been replicated with different presentation techniques (Jainta et al., 2017), the underlying visual processing of monocular information may differ across different methods and should be carefully explored in future work.

Another avenue for future research concerns the empirical investigation of neural correlates of binocular vision and binocular fusion during written language processing. While we know a great deal about the areas of the visual cortex which are sensitive to binocular disparity – indeed to the level of receptive fields of individual neurons –the task of characterising the functional units of conscious, unified binocular perception remains a challenge. Indeed, no research so far has investigated the neural correlates of binocular fusion in the context of reading, or indeed, single-word identification. This means that our understanding of the cognitive and neuropsychological bases of how individuals represent and process written language is fundamentally limited, which in turn curbs our potential to seek remediation for the reading difficulties experienced by those with impairments in binocular visual function (e.g. amblyopia, strabismus, or after macular disease or stroke).

It is, therefore, now important to take further steps towards developing comprehensive understanding of the neural correlates of binocularity during reading. Such a research initiative would be timely, given the recently developed experimental approach of co-registration. For example, the experimental technique of simultaneously recording eye movements and event-related potentials (ERPs) has unique advantages over the use of each individual method alone. Co-registration has the potential to help researchers obtain an in-depth understanding of visual and cognitive processes that unfold simultaneously during each fixation in reading (Dimigen, Sommer, Hohfeld, Jacobd, & Kliegl, 2011; Henderson, Luke, Schmidt, & Richards, 2013). Therefore, future research would ideally employ techniques such as co-registration in order to understand the neural basis of binocular visual function during written language processing.

Another issue that is likely to be of interest both for future research and clinical practice concerns the degree to which findings from participants with normal binocular visual function generalise to individuals with visual problems. For example, amblyopia – a developmental condition where one of the eyes fails to achieve normal visual acuity in spite of treatment and correction – is among the most common binocular vision deficits experienced in childhood (Simsons, 2005). Its worldwide prevalence is estimated by the World Health Organisation to be about 5% in children under 15 years old (Aldebasi, 2015; Fu, Li, & Liu, 2014). Amblyopia is also among the most common causes of unilateral vision loss in adults, and is known to impact and exacerbate other visual disorders that may occur throughout the lifespan (Webber & Wood, 2005). In the past 35 years, a great deal of research has been aimed at understanding the sensory deficits experienced by individuals with amblyopia and the corresponding neural deficits, typically with a view towards identifying the nature and cause of the condition (Levi, 2013). In contrast, very little systematic empirical work has been dedicated to investigating the consequences of amblyopia for reading development and reading performance in childhood and adulthood. Some existing findings have suggested that performance at standardized tests of reading speed is lower in children with amblyopia than in controls (Stifter, Burggasser, Hirmann, Thaler, & Radner, 2005). Critically, the deficits in reading speed were found to persist even if visual acuity did not differ between the amblyopic group and the control group, supporting earlier work by Zurcher and Lang (1980). Additionally, an eye-tracking study with adults conducted by Kanonidou, Proudlock, and

Gottlob (2010) found a slower reading rate, longer fixations and an increased number of regressions for amblyopes, relative to control participants. Importantly, reading was impaired in amblyopes regardless of whether they read binocularly, with the amblyopic eye or with the non-amblyopic eye.

It appears, therefore, that amblyopia significantly affects the ability to read fluently in both children and adults, and that standard treatment addressing parameters such as stability of fixation and low contrast perception may not be sufficient to address deficits in more complex cognitive tasks (Simmers, Gray, McGraw, & Winn, 1999). What is less clear, however, is how amblyopia influences foveal and parafoveal processing during reading. No existing empirical work has addressed this question with suitable experimental stimuli, and it is therefore not clear whether deficits in binocular vision translate to differences in word identification processes and lexical access during direct fixation, or in the ability to efficiently extract information from parafoveal text. Future research would need to address this concern in order to establish the degree to which visual and cognitive processes underlying reading are interconnected and interdependent in individuals with binocular vision deficits.

5.7 Conclusion

Reading is an extremely valued skill in a highly technological society such as ours. It not only allows individuals to successfully perform many day-to-day tasks, but also to develop and flourish, both professionally and socially. It is, therefore, no surprise that reading is the cornerstone of Western education, or that over a century of scientific investigation has been devoted to understanding the cognitive underpinnings of written language processing. What is surprising, however, is that the role of binocularity –a fundamental characteristic of the human visual system –is not fully specified in the context of reading. This is a crucial limitation in our current understanding, because during each and every typical reading fixation, the binocular visual system is engaged in binocular fusion, or, in other words, in delivering a stable, unified perceptual representation of the written text to the language processing system. And while sophisticated computational models of oculomotor control in reading provide detailed accounts of how cognitive processes drive the forward movement of the eyes through the text, little is known about the interaction between these processes and binocular vision.

In this context, the empirical work presented in this thesis adds to the growing literature on binocular vision in reading and addressing questions that had previously not been the subject of thorough scientific investigation. The preceding chapters have presented work that aims to contribute to the comprehensive understanding of motor and sensory fusion processes during reading. They have also explored the advantages of binocular vision for foveal and parafoveal word identification, and have provided novel insight into the precise aspects of written text processing that rely on binocular vision in order to be executed efficiently. Overall, this thesis serves to address – at least partially – the growing need for consistent, comprehensive research into binocularity with relation to reading. Thus, the work presented here brings the field a step closer to bridging the gap between our existing understanding of human binocular vision and the conscious visual experience of a single, unified percept upon which written language comprehension is fundamentally based.

Appendix A

List of sentences used in Experiment 2 (Chapter 3)

1. Alice waters those exotic white *flowers/orchids* every five days during warmer months.

2. George always makes lovely fresh *coffee/crepes* when Jenny comes back from running.

3. Lizzie bought that purple silky *dress/cloak* while shopping with Laura last Friday.

4. When police officers went inside that large *house/crypt*, they found more clues.

5. Julie often drank tasty fresh *orange/lychee* juice during that long summer trip.

6. During cold months, Katie wears that *yellow/pastel* woollen scarf when walking outside.

7. During rugby games, fans always *cheer/ovate* when their team scores more points.

8. Those shallow lakes turned into thick *nasty/fetid* swamps after another long drought.

9. Roses were planted around father's *garden/vinery* years before those houses were built.

10. Those clever young thieves *quickly/niftily* covered their tracks before they were seen.

11. Anne never liked John's cousin, whose *stupid/oafish* remarks upset everyone last night.

12. Kings always fought with their loyal *friends/vassals* beside them, thus gaining power.

13. Some older liberal party members *think/opine* that civil laws need more changes.

14. Mary worried that extreme heat could *damage/deform* those rare delicate black pearls.

15. They feared their aunt's stern *voice/glare*, which always made them very nervous.

16. This business plan could *bring/incur* large costs unless someone offers expert advice.

17. After last night’s party, Harry managed some *broken/fitful* sleep until sunrise came.

18. Jack could hardly hear Lilly's *quiet/reedy* voice after closing that heavy door.

19. Bold young cowboys often chase wild *horses/dingos* across those vast desert lands.

20. That small ship cruised along another *river/fjord* while tourists took more photos.

21 Their mother seemed very *happy/jolly* after finding those lost letters last night.

22. That greedy mayor made plans without *thought/scruple* about people from remote areas.

23. Alex would need better trading *profit/acumen* before opening another large bike shop.

24. Many people face this common *problem/pitfall* when changing their mobile phone number.

25. After that debate, Jake could never *accept/recant* other people's views about religion.

26. Their maths teacher would always *explain/iterate* complex rules until they were clear.

27. They never learned that critical *story/axiom* which affected their exam results poorly.

28. Locals often drink from those *little/turbid* streams, but tourists should avoid that.

29. Anne's twin girls both have long *black/mousy* hair framing their round faces.

30. Track runners usually have *strong/sinewy* lean muscles after training for many years.

31. That famous French chef *cooked/glazed* fresh carrots, then served them with sauce.

32. They were driving through that lovely *town/glen* when their engine suddenly seized.

33. Linda knew that famous young *doctor/sleuth* because they studied together years ago.

34. While Alex finds those books very *scary/vapid*, John really loves reading them.

35. With that smile Kelly easily *tricks/coaxes* others into doing very boring work.

36. After coming home, they noticed some *sweet/acrid* smell coming from their kitchen.

37. Bill looked across that narrow *field/chasm* where several small houses once stood.

38. The young couple felt that their *lunch/tryst* could have been planned better.

39. Many ideas vary between different pagan *groups/covens*, often even among single members.

40. Many staff members will *bother/accost* John with questions after that budget meeting.

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