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**Binocular strategies in reading and non-reading visual tasks:
from oculomotor behaviours to higher cognition**

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Abstract

Humans use two eyes to extract selected information from the real world and deliver it to the human brain for higher cognition and the perceptual system. However, the two eyes are not always aligned. Eye movements are produced and the eyes accommodate in response to different visual stimuli. Studies on binocularity have reported its importance in accord with specific visual processing requirements. The main aim of this thesis is: how does binocular performance correspond to higher cognition in visual perception?

This thesis explores how the two eyes coordinate their efforts to respond and adapt to cognitive activity, through oculomotor behaviours. The physical disposition of the eyes can be a part of cognitive processing, as an ‘embodied’ process of visual perception, that facilitates visual information processing. Therefore, we investigate binocular strategies in both reading and non-reading visual tasks, from oculomotor behaviours to higher cognition, to understand its implications for systematic and strategic processing in visual perception.

In the reading part, we first investigate the two left-to-right orthographies, English and Chinese. We analyse small temporal non-alignments between the two eyes’ with nine patterns of temporal disjugacy and find that the distribution of small asynchronies of binocular fixation accord with ocular prevalence (Chapter 2). Such asynchronies are predictive of ocular prevalence, in which input to the left eye is prioritized in conscious perception of a fused visual stimulus for targets in the left visual field and right-eye input is prioritized for targets in the right visual field. Then, this typology is further explored in two right-to-left orthographies, Arabic and Hebrew (Chapter 3). We found reading behaviours of these Semitic languages resemble this advantageous switching of ocular prevalence, but mirror the pattern of left-to-right orthographies due to the change of reading direction.

In the non-reading tasks, we first investigate binocular adaptive behaviours in two reading-like tasks (i.e. reading lines of numbers). We specifically explore how the visual system reacts and adapts to continuous text-background contrast (chapter 4) and how the visual system reacts and adapts to the level of faintness of the stimulus (chapter 5). In the contrast experiment (chapter 4), we found systematic adaptation of binocular vision in response to the contrast change, with an overall crossed tendency of binocular fixations (i.e., right eye's fixation to the left of the left eye's), as well as disparity-related behaviours as the contrast became lower and reading difficulty increased.

On the other hand, in the experiment with variation of the level of faintness of the stimulus (chapter 5), we also found systematic adaptive binocular behaviours with an overall crossed tendency of fixations, but with increasing distribution of uncrossed fixation pairs (i.e., right eye's fixation to the right of the left eye's) as the level of blurriness of the text stimulus increases and reading difficulty increases. Our findings are consistent with previous research but reveal that the adaptation is a strategy rather than the effect of fatigue, and that this strategy operates very flexibly and specifically with respect to location. The overall effect of the visually adaptive behaviours in these two experiments suggests that the two eyes coordinate to adjust through very peripheral muscle-driven movements of the eyes and all the way to higher cognitive processing, in response to contrast change and blurring of the stimuli, for better visual quality and performance in different conditions for visual perception.

Finally, we conducted two illusion-related experiments, including a visual illusion created by depth information (chapter 6) and a motion-based illusion with Plateau's Spiral (chapter 7). We replicated Murray et al.'s (2006) experiment with far and near spheres and investigated how the visual system reacts and responds to a visual illusion created by depth information as a cue for

judgement of perceived size (chapter 6). Our results support Murray et al.'s (2006) interpretation of their data only partially and suggest an alternative interpretation to their influential experiment: Murray et al.'s apparent VI correlate of the size illusion may be partially attributable to larger binocular fixation disparities on the back sphere (i.e. sizeable non-overlap between the retinotopic mappings from the left and right eye).

In another visual illusion experiment, we investigate how the two eyes would respond to stimuli that produce a motion-based illusion of depth, given that such stimuli produce not just an aftereffect but different perceptions during the stimulus. We found general similarities in processing clockwise and anticlockwise spinning spirals, in terms of vergence movements. However, our experiment shows a remarkable difference in the binocular strategies in processing at different spatial locations. It indicated hemispheric specialisation and projection during viewing an illusional stimulus, and corresponding binocular strategies for visual processing. Perception can be manipulated by hemisphere-based higher cognition controlling the oculomotor musculature, allowing the hemispheres to generate their own most appropriate input, when viewing a visually challenging stimulus, Plateau's Spiral.

In summary, this thesis investigates binocular strategies in visual perception in response to different stimuli and conditions in both reading and non-reading tasks. We found systematic and harmonious behaviours from peripheral muscle-driven movements of the eyes that correspond to the cortical processing that contributes to cognition, showing the flexibility of the visual system in different modes of operation, from peripheral binocular movement all the way to higher cognitive processing.

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Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

(Ruomeng Zhu)

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Chapter 1

Introduction

1.1 General introduction

The human visual system receives and processes the visual information for the brain. The two eyes are the direct source of our visual information for further processing in related visual cortex; selected information from the real world is delivered to human cognition and the perception system through eye movements, as one of the primary methods (Henderson, 2013). It has long been found that cognitive requirements can influence eye movements and binocular control can also influence cognitive activity vice versa (Yarbus, 1967; Nelson & Loftus, 1980). Thus, the ability to control and manipulate various eye movements can influence the visual quality of the stimuli perceived in the human brain. The question here to ask is: how would binocular performance correspond to higher cognition in visual perception? The physical disposition of the eyes could be part of cognitive processing, as an ‘embodied’ process of visual perception, that facilitates visual information processing.

The critical concept of binocular control has been highlighted in research on visual perception; how the eyes perform and coordinate corresponds to changes in sensitivity of the visual system and the strategies of the related visual cortex (Fisher et al., 2017). This collaborative control of the eyes, through vergence movements (Kirkby et al., 2008; Nuthmann & Kliegl, 2009), has been reported to be systematic and strategic. It has been investigated broadly in both reading (Rayner, 1998; Rayner et al., 2005; Rayner et al., 2012; Liversedge et al., 2016) and non-reading tasks (Land, 2006; Land, 2009; Schütz et al., 2011; Foulsham, 2015).

We will investigate the characteristics of the binocular collaboration (i.e., how do the two eyes coordinate their efforts) by exploring how the eyes respond and adapt to critical visual tasks. Specifically, the present thesis explores binocular strategies in visual perception during reading and non-reading tasks, under various perceptual conditions with a wide range of visual stimuli, including different orthographies and visual scene stimuli.

1.2 Understanding eye-movement: dynamics and mechanisms

1.2.1 Fixations and saccades

Our eyes receive the information while resting on the attentive objects for a certain period of time, around 150 to 500 ms (Rayner et al., 2012), this almost immobile state is called fixations. Between the fixations, there are ballistic rapid eye movements which suggest jumping of the eyes called saccades. The pattern of fixations and saccades is typical in perceiving static stimuli to extract visual information with relative efficiency (Rayner, 1988). In the reading task, the two eyes move progressively but also with regressions and return sweeps in between. The direction of eye movements toward the left and the right are adjusted and accommodated through visual related muscles, with lateral rectus muscle moving towards the nose (associated with faster acceleration) (Robinson, 1964) and abductive saccades to move away from the nose. These physiological mechanism from the muscle-driven perspective suggest potential difference of the left and the right eye coordination. During the binocular coordination, variation could reveal through vergence and disparity. Similarly, different reading direction to process the text information could be influenced as well, either from the left to the right or verse vice.

1.2.2 Binocular coordination

Binocularity, as a critical part of the human visual system, functions fundamentally in visual information processing, together with all the physiological and neurological mechanisms (Rayner, 1998). The advantage of binocular coordination over monocular vision has been reported by many researchers, in both reading (Heller & Radach, 1999; Jainta & Jaschinski, 2012; Paterson, 2014) and non-reading tasks (Blake et al., 1973; Blake et al., 1981). It has been suggested that both fixation disparity and vergence adjustments are important parameters of binocular coordination (Jainta & Joss, 2019). The visual system works as a whole to achieve appropriate collaboration in normal binocular vision.

Binocular fusion is generated through cortical combination of single percept from both eyes with the overlap images from the left and the right visual fields (Stidwill, & Fletcher, 2017). It requires two eyes collect the visual information and transfer it to the brain through neural pathway and further analysis and perception from the neural processing system. During the process, the ocular muscles and the motor control system would integrate to facilitate the process by fusing the images appropriately and generating proper eye-movements.

The visual cortex integrates the two images relying on retinal correspondence, which requires binocular collaboration through vergence control. The vergence system also uses fixation disparity to monitor the alignment and misalignment of visual axes and operate the lines of the sight. The visual system constantly adjusts and adapts when processing the information to contribute to visual perception.

1.2.2.1 Panum's fusional area

Panum (1858) has illustrated that single vision is created through the corresponding retinal points to the objects of one eye and similar small areas around for that in the other eye. This single

vision is obtained within limited range to maintain the stereoscopic vision and avoid diplopia, which is called Panum's fusional area. It allows single perception, aligning with vergence adaptation system and regarding operation of fixation disparity (Harrold & Grove, 2021).

Visual stimuli beyond the Panum's area would be seen double. As shown in Figure 1.1, the concordant images produced from the corresponding retinal points of the objects will fall on the horopter (which is an imaginary arc when all the binocular points show zero disparity), but a single binocular image is still possible to be formed if those points fall within Panum's fusional area (Stidwill, & Fletcher, 2017). The range of Panum's fusional area suggests the potential of vergence movement in the individuals to maintain a single image. They both contribute to stable binocular vision.

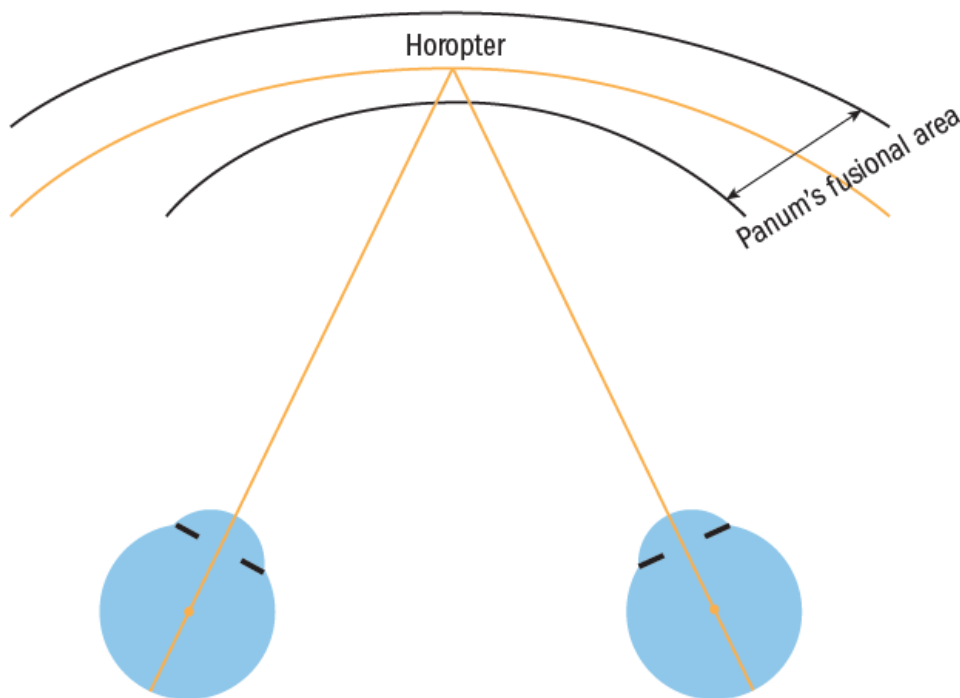


Figure 1.1 Panum's fusional area (beyond which the vision is diplopia) and horopter (Black & Arbon, 2020).

1.2.2.2 Vergence

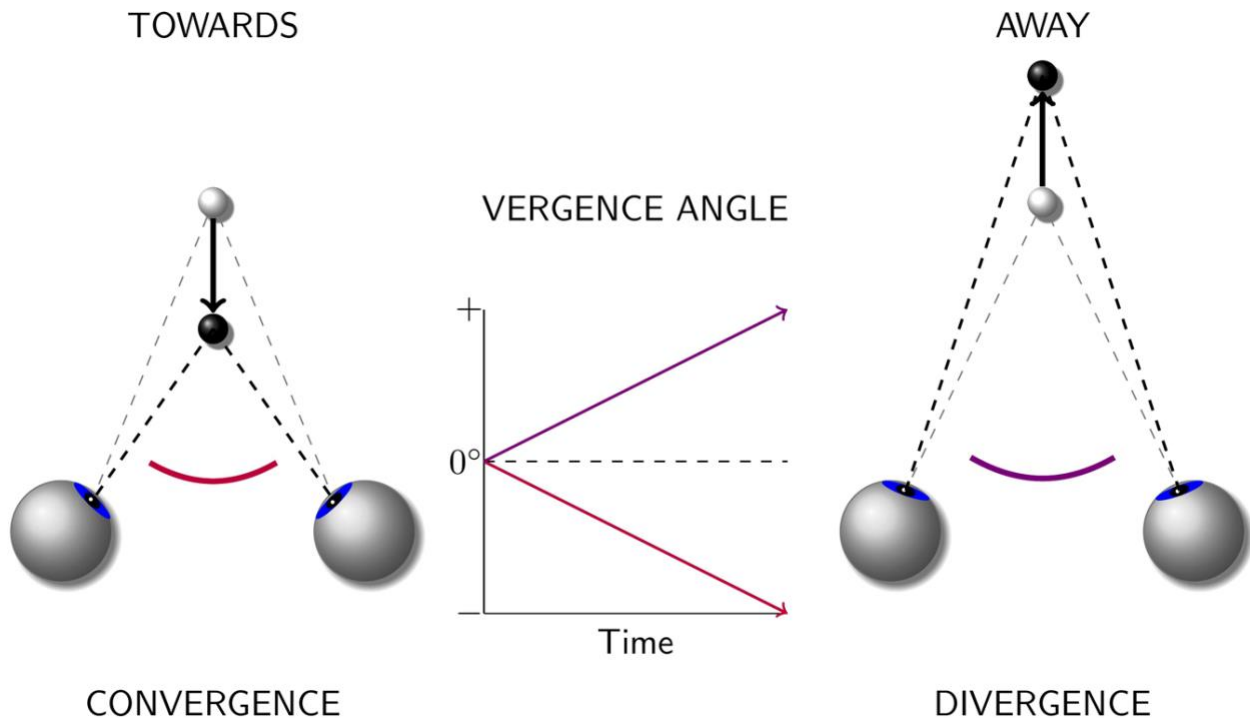


Figure 1.2 *Diagram of convergence and divergence. (Giesel, 2019). Convergence suggests both eyes rotate inwards while divergence with outwards.*

Vergence movements are critical parts of the visual perception, including horizontal and other directions of rotations of the two eyes (e.g., vertical or cyclovergence) (Howard, 2002). This thesis will focus on horizontal vergence movements. As indicated in Figure 1.2, the horizontal vergence movements contains convergence (both eyes rotate inwards) and divergence (visual axes move outwards) (Howard, 2012). Normal binocular vision requires fusional vergence movements to adjust and accommodate to avoid retinal images blur (Büttner-Ennever, 1988). Previous studies have shown that vergence responses are required to align the foveae in response to properties of binocular neurons, to function as a whole in primary visual cortex on the target (Candy & Cormack, 2021). It has also been argued that vergence eye movements are considered

as cues for subsequent sensory binocular fusion and later cognitive processing, such as reading processing (Blythe et al., 2010; Jainta et al., 2014; Jainta et al., 2015), depth perception and absolute distance (Linton 2020; Linton, 2021).

The dynamic nature of the vergence system, driven by binocular disparity and is considered as oculomotor adjustments for relative optimal retinal activation corresponding to the viewing objects (Bharadwaj & Candy, 2009). However, the specific coordination of vergence with other dynamics of visual systems such as accommodation and neural circuit is still much to understand (Candy & Cormack, 2021). The vergence system indicate disparity-tuned processes, binocular disparity is also recognized as the primary causes for vergence change (Kaestner et al., 2022). Issues has raised in recent year of the functions of vergence movement as ‘cues’ of visual perception (Linton, 2021). Nevertheless, vergence is generally adjusted in response to visual stimuli in the perception. In this thesis, we will discuss how vergence and disparity serve as part of visual system function, in accordance to further higher cognition.

1.2.2.3 Disparity

Fixation disparities, induced by the position of the two eyes to project the information across the two foveas (Shillcock et al., 2010), reveal the spatial variability of binocular fusion and provide an optimal combination from the fovea to the related visual cortex. Different types of disparity have been frequently observed in both reading and non-reading tasks (Kirkby et al., 2008), in terms of magnitude and nature, indicating how binocular vision could influence task performance. Categories of binocular disparity includes crossed and uncrossed fixation pairs. The left (LE) and right eyes (RE) frequently fixate at different points in the viewing task, which presents an

uncrossed fixation where the LE fixates to the left of the right eye; and a *crossed* fixation disparity when it is the switched position to the right.

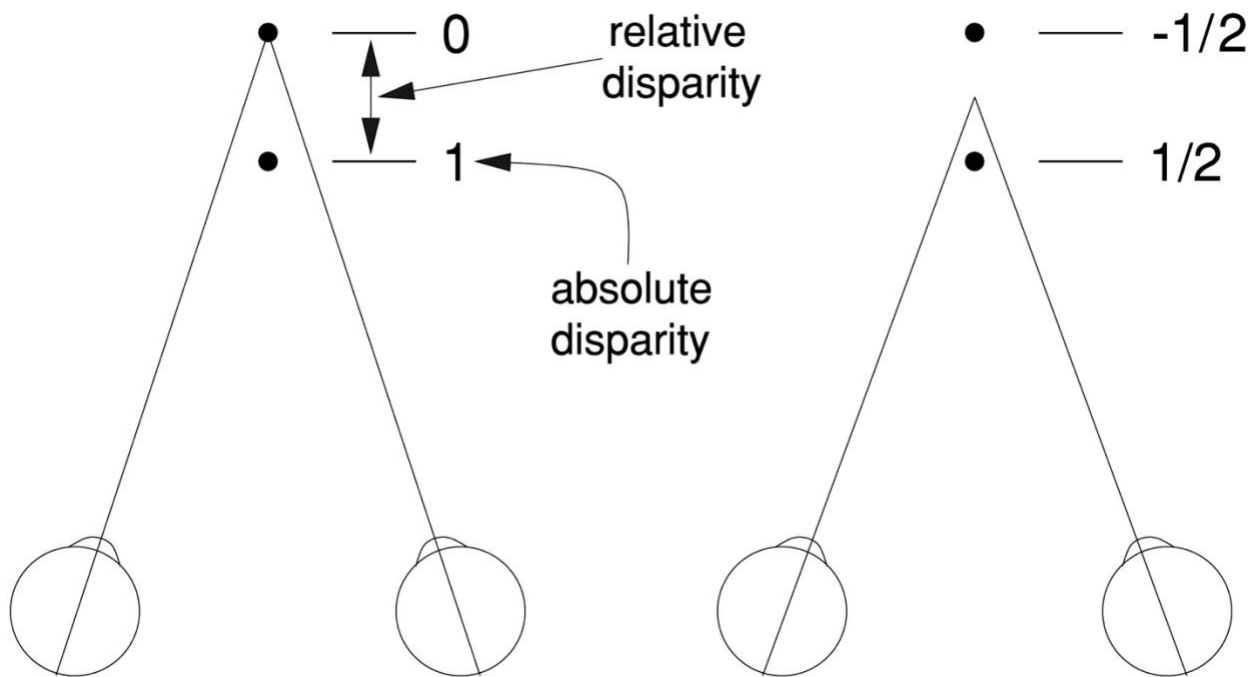


Figure 1.3 Relative and absolute disparity. (Neri, Bridge & Heeger, 2004). Relative disparity remains constant based on angle of two static objects in space, while absolute disparity shifts according to the alignment of left and right visual axes (as it shows in the difference of the left panel and the right panel).

Other stimulus-based dichotomies include absolute and relative disparity. Absolute disparity is the difference of the left and the right retina in the amount of disparity to align the visual axes; while the relative disparity is the constant comparative angle of two static objects in space (Candy & Cormack, 2021). Absolute and relative disparity is also being processed differently. Two types of disparities are being processed differently by distinctive mechanisms. The earlier visual areas in the visual pathway respond to both, while the later cortical processing develops differential extraction starting from the cells of V1 which are sensitive to absolute disparity and then further processing of relative disparity in higher visual processing areas (Kaestner et al., 2022). In addition, the ventral stream responds to both relative and absolute disparity, the dorsal

stream mainly to absolute disparity (Neri et al., 2004) (see more specific explanations in Chapter 8).

Research on reading suggests an integral role of binocular coordination in written language comprehension (Kirkby et al., 2011) and the importance of collaborative eye movement control on such a complex and cognitively demanding task (Nikolova, 2018). Binocular advantages in foveal processing are also reported in the reading process (Jainta et al., 2010; Paterson, 2014), suggesting the benefit for binocular over monocular reading to influence higher cognitive processes. Though binocular reading behaviours vary across different languages and their orthographies (Eviatar, Ibrahim, & Ganayim, 2004; Eviatar, Ibrahim, Karelitz & Simon, 2019; Hsiao, 2017), researchers have still found both universal and language-specific features in recent years (Hsiao et al., 2018; Liversedge et al., 2016).

Studies on non-reading tasks have also reported great variation, depending on the experiment. Collewyn et al. (1997) investigated the binocular fixation point on a horizontal plane, suggesting that the control of the gaze shift, in terms of both vergence and version, differed for different targets, implying a tendency for disconjugate movement (Kirkby et al., 2008). Though finding dissociated horizontal binocular eye movements, the result with only a small vertical disparity has been questioned by other researchers (Enright, 1998). Enright (1998) reported an asymmetry in both initial and final vergence and showed that one eye would typically produce a better alignment with the location of the new target due to a binocularly unbalanced saccade, while the other eye, would deviate and achieve its foveation later than the predominantly programmed eye. Unbalanced binocular fixations were also discovered by Cornell et al. (2003) by exploring binocular fixation under natural viewing conditions. The results showed a fast vergence movement when the eyes

move between a near target and a far target, causing errors of binocular fixation, including underconvergence and underdivergence in typical readers.

Nuthmann and Kliegl (2009) suggested variation of crossed and uncrossed distribution can be attributed to factors such as individual differences and experimental settings. Yang and Kapoula (2003) asserted that “the binocular coordination of saccades is not built-in, but is a process developing through visual experience and learning” (p. 560). The specific collaboration and manipulation of disparity might imply that viewers optimize for the viewing condition by exercising a degree of independent control over their two eyes. Shillcock et al. (2010) proposed that binocular disparity could be a functional and adaptive process of the two eyes to facilitate processing under a range of different viewing conditions, rather than just being reflective of the visual context. According to the Shillcock and colleagues (2010), crossed fixations show a clear advantage in binocular fusion with greater effectiveness and efficiency in general, whereas uncrossed fixation disparities facilitate processing in viewing conditions that make fusion difficult. We will investigate this further in the experiments with non-reading tasks.

1.3 Visual pathway and foveal splitting: collaboration and accommodation

The basic anatomical separation of the two cerebral hemispheres has implications for the early stages of cortical processing. The received information is functionally divided at the midline. The hemispheric difference, therefore, represents potentially split foveal processing for visual perception, and therefore may facilitate our understanding of higher visual processing (Shillcock et al., 2000). Theories of foveal splitting have proposed that the left and right cerebral hemispheres cooperate chiefly across the corpus callosum during visual processing (Shillcock et al., 2010). When fixating the visual stimuli, the information from the right visual field would be projected to

the left hemisphere via the right of fixation and the information from the left visual field, on the other hand, is projected to the right hemisphere (Lavidor & Walsh, 2004).

Evidence has been found in hemianopia (Trauzettel-Klosinski & Reinhard, 1998; Miki et al., 1996; Reinhard & Trauzettel-Klosinski; 2003) against significant bilateral foveal projection. It has been also investigated in split-brain patients (Brysbaert, 1994; Corballis & Trudel, 1993; Fendrich et al., 1996) who experience greater difficulty in processing foveated stimuli due to dysfunctional interhemispheric communication. Lavidor, Hayes, Shillcock, and Ellis (2004) reported different effects in reading separately for the left and right halves of centrally fixated words. Hsiao and Shillcock (2005) also explored similar influences based on foveal splitting when fixating single Chinese characters with different structures and found naming-time differences. Some neuroimaging studies also provide evidence in support of the split foveal theory in normal reading (Portin et al., 1999). Hsiao et al. (2007) observed a stronger effect in an EEG study of right fixations with phonetic component words in the left hemisphere than the other side in Chinese. Nonetheless, claims regarding splitting foveation remain controversial, Jordan and colleagues (2009, 2010) presented the evidence against it with different experimental constraints (Ellis & Brysbaert, 2010).

Poffenberger (1912) observed differences of the two sides of the visual field in receiving sensory input and in the motor response in contralateral and ipsilateral conditions. Toosy et al. (2001) described stronger effects of monocular stimulation from the contralateral hemisphere in an fMRI study. Obregón and Shillcock (2012) report a functional contralateral bias during reading, specifically the advantage of contralateral projection over ipsilateral pathways in lexical processing. Figure 1.1 shows a model of how the two pathways split when processing the stimuli. Though with slight controversy, later research has still found evidence to support the splitting

behaviour in the human fovea cross-linguistically (Hsiao et al., 2018; de Almeida et al., 2020). The advantageous processing from foveal splitting will be discussed further in the chapters about binocular reading behaviours (i.e. chapter 2, 3, 8).

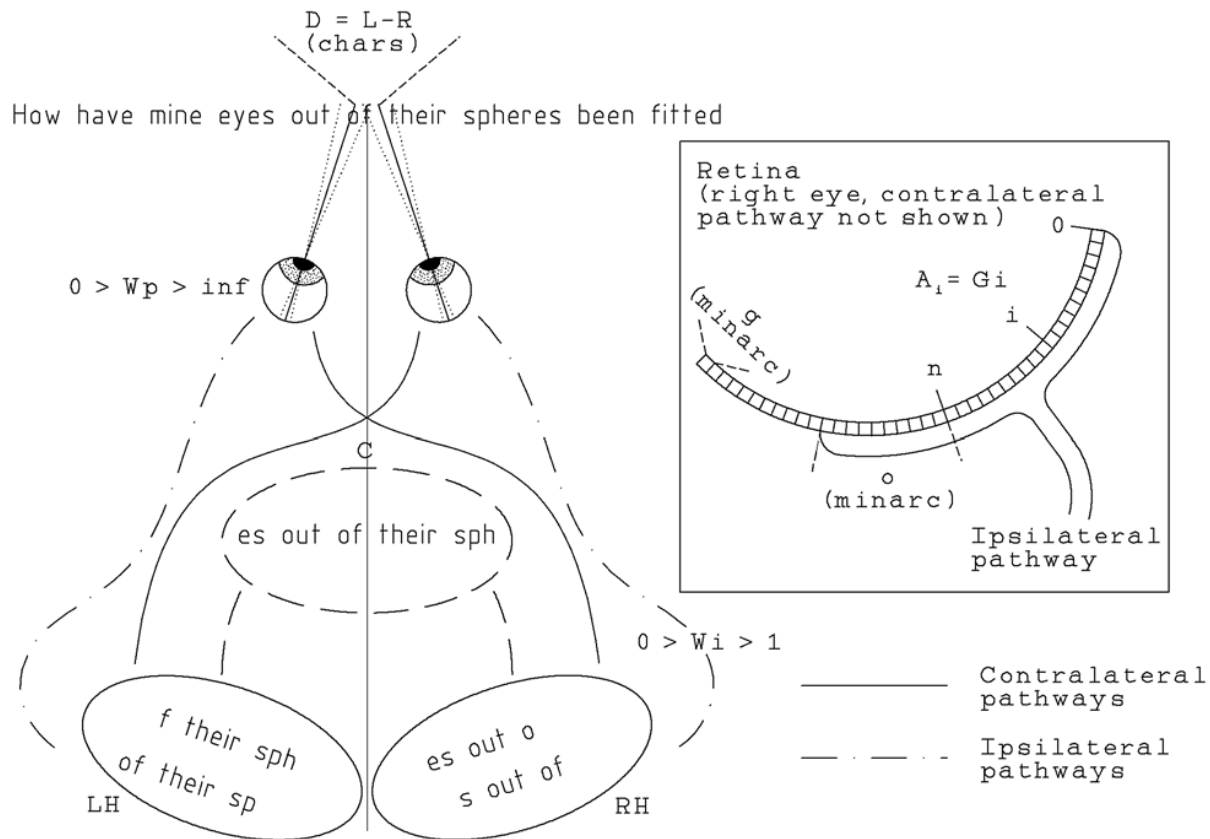


Figure 1.4 A model of activation in the visual pathways (Shillcock et al., 2010). The visual information being split to the left and the right eyes and propagated to the cortex via contralateral (e.g., right eye to left hemisphere) and ipsilateral (e.g., right eye to right hemisphere) pathways.

The debate has gone on for a long time as to whether the human fovea is neatly vertically divided and exclusively contralaterally projected to the visual cortex. During that time the study of retinotopic mapping has continued and the relevant technology for has improved (Tyler et al., 2005; Schira, Tyler, Breakspear & Spehar, 2009; Schira, Tyler, Spehar & Breakspear, 2010; Schira, Wade, & Tyler, 2007). However, such studies are typically concerned with cortical magnification

and anisotropy and with relations between V1, V2 and V3 and do not discuss the issue of foveal splitting.

Two later reports directly address the issue and confirm the position that foveal splitting can be considered as exact, with cognitive consequences for conscious visual processing. In the first, Schira (2018) asks “Any double representation of the fovea? If there are ipsilateral connection from the eye to the LGN, why is there no cortical representation?” and provides a reanalysis of data from Bunt and Minckler (1977) and Fukuda et al. (1989). In the second, Strother, Coros and Vilis, 2016) report fMRI data from a visual word recognition study involving stimuli divided over the hemifields. They report significant effects of word repetition in a previously reported visual word form area (VWFA) in occipitotemporal cortex, which represents hemifield-split words as whole units. They also report a more posterior occipital word form area (OWFA), which represents word form information in the right and left hemifields independently and is thus both functionally and anatomically distinct from the VWFA.

Overall, we can say that the conclusion of earlier research still stands—that the retinotopic projections into the cortex in the earlier parts of the visual pathway respect foveal splitting. In the earlier literature, it has always been clear that visual areas more removed from V1 are more likely to contain receptive fields that involve both hemifields, albeit typically with a stronger contralateral response. Furthermore, intact representation in V1 is known to be necessary for conscious perception. The issue of specifically lexical processing of words in one, other or both hemifields has been approached more recently from the perspective of the question of parallel processing of more than one word; White, Palmer, Boynton and Yeatman (2019) argue in favour of a more anterior processing bottleneck, but this picture seems to be still consistent with claims regarding the split fovea.

1.4 Ocular prevalence and ocular dominance

Ocular *dominance* is usually discussed as the dominant behaviour of engaging one eye's input completely when processing real-world information (Porac & Coren, 1976). While dominance in the population tends toward to the right eye (Hillemanns, 1927), the function of the dominant eye remains unclear in vision (Mapp et al., 2003). Effects of ocular dominance are associated with motor control, which leads to density of connectivity and therefore more finegrain control which might affect saccadic launching (Tagu et al., 2018).

On the other hand, ocular *prevalence* has been typically referred to as quantitatively resolving stereo-disparate images (cf. Kommerell, Schmitt, Kromeier, & Bach, 2003). Kommerell et al. (2003) find that the two eyes tend to be preferred equally among different individuals. Kromeier et al. (2006) also report that ocular prevalence is compatible with high stereo acuity at small stereo disparities.

It has also been discussed recently in a wider concept as one eye's input being prioritized in binocular fusion, in less 'stereo-disparity'-related conditions such as text stimuli (cf. Shillcock et al., 2010). The combination of inputs from the two eyes would be less relevant to depth perception, but more appealing to the adjustment to—and adaptation of— viewing angles as fixating the left side or the right side of a line of text. The slight skewness of one eye during processing raises the computational question about how the eyes fuse the input to the best advantage and how ocular prevalence (the “graded quantification of the balance between the eyes”—Kommerell et al., 2003, p. 1397) could improve the division of labour between the two eyes.

The physical constraints on the two eyes in binocular fusion could be associated with anatomical and physiological human diversity such as size and shape of the eyeball, which may naturally cause prevalence based on peripheral space around the visual target (Schwartz, 1977).

The input to one or other eye may be prioritized in the higher, binocularly-fused visual processing, implying swift control of cortical activation to process real-world information. We will continue to investigate how this asymmetry of ocular prevalence plays out in the reading process, with left-to-right orthographies (chapter 2) and right-to-left orthographies (chapter 3).

1.5 Reading cognition

Reading, involving both vision and linguistic processing (Liversedge et al., 2016), is a complex psychological process which requires a great accommodation of eye movements to produce optimal behaviours (Wahlberg-Ramsay et al., 2012). Binocular coordination during reading has become an important theme in reading research in the last two decades (e.g., Liversedge, White, Findlay, & Rayner, 2006; Shillcock, Roberts, Kreiner, & Obregón, 2010). At the same time, researchers have been increasingly interested to compare reading behaviours in different languages and their orthographies (e.g. Hsiao, Shillcock, Obregón, Kreiner, Roberts, & McDonald, 2018; Liversedge, Drieghe, Li, Yan, Bai, & Hyönä, 2016);

1.5.1 Reading in English vs. Chinese

Some research has focused on English and Chinese, which are languages both read from the left but with quite different orthographies. Chinese orthography is considered logographic, or ideographic. It is visually denser than English (cf. Hsiao et al., 2018). Its greater informational density elicits smaller saccades and longer fixations (cf. Hsiao, 2017; Liversedge et al., 2016), compared with English. Ho and Bryant (1999) suggest learning to read English and Chinese requires different visual skills. Similarly, McBride-Chang, Tong and Mo (2015) propose that reading Chinese co-opts more regions of the brain, compared with alphabetic texts. Despite such

processing differences, researchers have also proposed commonalities—or universals (e.g. Feng, Miller, Shu & Zhang, 2009). Sun, Morita and Stark (1985) reported similar patterns of saccades and fixations in the two orthographies. Liversedge et al. (2016) reported putative universal effects concerning word frequency, word length and word predictability across English, Chinese and Finnish.

Cross-linguistic research on binocular coordination in Chinese and in English has mainly been concerned with the *spatial* characteristics of eye-movements and with binocular fixation disparities during reading (e.g. Hsiao et al., 2018; Kirkby, Webster, Blythe, & Liversedge, 2008; Liversedge et al., 2006; Shillcock et al., 2010), specifying the location of the two eyes' fixations. Readers are assumed to coordinate their eyes to optimize higher visual processing. How is this optimization achieved and how might it be affected by the characteristics of the language and its orthography (cf. Hsiao, Shillcock, Obregón, Kreiner, Roberts, & McDonald, 2018; Liversedge, Drieghe, Li, Yan, Bai, & Hyönä, 2016)? How much is language-specific, how much is universal?

In reading, binocular fusion is crucial to this process and must involve deciding how much higher visual processing should rely on the input specific to each eye. This 'ocular prevalence' has typically been discussed in terms of quantitatively resolving stereo-disparate images (cf. Kommerell, Schmitt, Kromeier, & Bach, 2003) but it is a wider, subtler issue of combining similar inputs (Shillcock et al., 2010). How is this fluid division of labour between the eyes mediated? Hsiao (2017) investigated spatial binocular disparities with *temporally conjugate* fixations (i.e. fixations in which the right and left eye both start and end their fixations at the same time.). She reports (chiefly quantitative) similarities and differences across the two languages. However, *temporal disjugacy*, the small-scale temporary unyoking of the two eyes' fixations in time, has been less explored. Therefore, in **chapter 3**, we will further explore non-alignments in the timing

of the start and end points of the fixation of the two eyes and report binocular fixation data in reading English and Chinese in terms of small temporal asynchronies between the two eyes during multiline reading.

1.5.2 Reading in Hebrew vs. Arabic

Hebrew and Arabic, both as right-to-left orthographies (RTLOs), have been studied comparatively in reading research. Arabic and Hebrew are alphabetic, Semitic languages. They share similar morphological, semantic, and syntactic structures (Shimron, 2003). Both are read from right to left (within the word and within the sentence) and are processed through a roots-based system composed of three or four letters (Abu-Rabia, 2002; Abu-Rabia & Siegel, 2003). In both orthographies, some vowels and diacritics are ordinarily omitted in ‘unpointed’ versions of the text intended for skilled readers. Greater processing difficulty has been reported in reading Arabic compared with Hebrew (Brysbaert, 2019; Eviatar, Ibrahim, & Ganayim, 2004; Eviatar, Ibrahim, Karelitz & Simon, 2019).

Compared with English reading behaviours, Arabic and Hebrew show both similarities and differences (Frost, 2009; Frost, Kugler, Deutsch, & Forster, 2005; Hermena & Reichle, 2020; Jordan, Paterson & Almabruk, 2010; Velan & Frost, 2007). How might directionality affect reading? Since reports by Beaumont (1982) and Bradshaw and Nettleton (1983), it has been clear that there is typically a left hemisphere (LH) and right visual field (RVF) processing advantage for reading isolated words. In the relevant experiments on reading left-to-right orthographies (LTROs), words are approached from the left, meaning that their relatively more informative beginnings (a phonological fact grounded in speech perception, cf. Nooteboom, 1981) are initially parafoveally projected directly to the LH. This fact initially suggests that LTROs are optimal.

Deutsch, Frost, Pollatsek and Rayner (2000) report a comparable parafoveal facilitation by letters from Hebrew triconsonantal roots; Hermena, Juma and AlJassmi (2021) report a similar effect in Arabic readers. Thus, Arabic and Hebrew can also benefit from the relatively informative view of the beginning of the word. It will, however, be projected to the *right* hemisphere (RH). Ibrahim and Eviatar (2009) demonstrate a greater *left* hemisphere (LH) advantage for word recognition in L1 Arabic speakers/readers for Arabic compared with L2 Hebrew and L2 English. However, this hemispheric division of labour in word recognition does not mean that right-to-left scanning of Arabic and Hebrew is not optimal.

Instead, there may be a differential reliance on the LE and RE in the binocular reading of LTROs and RTLOs. In a RTLO, the difference is that it is the LE that is fixating the ‘previously seen’ text (in the predominant ‘crossed fixations’, in which the left eye fixates to the right of the right eye) and it is the RE that is obtaining the farthest lookahead in the upcoming text and projecting it contralaterally to the RH—a projection to the non-lexically specialized RH. Initially, it seems that the lexically privileged LH is not getting a direct, furthest parafoveal lookahead in RTLOs; this issue is orthogonal to the fact, reported by Jordan et al. (2013), of essentially mirror-image asymmetries of the perceptual span in the direction of reading for Arabic and English. Therefore, in **Chapter 4**, we will investigate the influence of ocular prevalence in reading RTLOs by comparing the data in reading LTROs, and further interpret how the evident hemispheric asymmetry in parafoveal lookahead may be reflected in the nature of right-to-left orthographic conventions.

1.6 Non-reading tasks

In this part, we will introduce some of the specific non-reading visual tasks involved in this thesis. We replicate a previous experiment but also investigate visual perception from a new perspective that has not yet been studied, exploring from binocular behaviours to an understanding of the visual system as a whole and the possible interaction with higher visual cognitive processing.

1.6.1 Depth intersection

In the real world, the visual system is actively engaging with objects, extracting depth information. A ‘retinotopic map’ can be produced by the visual pathways for higher-order information processing in the human visual system (Kersten & Murray, 2010). This rescales the visual configuration of the input onto V1 (Murray et al., 2006). There has been increasing interest in studying how the visual system reacts and responds to visual illusions. For example, in the Ponzo illusion, the eyes collect depth information as a cue for judgement of perceived size. Therefore, the brain perceives same-size objects differently due to their background (Kersten & Murray, 2010). Murray et al. (2006) carried out an experiment with two spheres, which have the same physical angular size but are perceived differently because of their 3D ‘hallway’ background. The back sphere in the experiment was reported to appear bigger and to occupy a larger part of the visual field compared with the front one. The size illusion is conveyed through perceived depth cues.

In Murray et al.’s influential experiment, the central question asked was at what point in the visual data path does the viewer take account of the depth information that leads to the visual illusion? They demonstrated that viewing an illusorily larger sphere created a correspondingly larger area of activation in V1. Their general conclusion was that the relevant processing was more peripheral than had previously been thought, although questions remained about the influence of

central processing. Murray et al. (2006) claim that their data suggest that the retinotopic representations in V1 are not simply the result of feedforward mapping from the retina but involve combining higher-order information from further along the visual pathway. They also claim that the representation is one that is geared to activity in the world, to knowing how large a thing is so as to be able to manipulate it.

What are the implications for the whole visual system? Are the eyeball movements also geared to this engaged, embodied interaction with the world, through the movements of the eyes (principally vergence)? Can other eye movements be interpreted in these terms? It has been known that binocular disparity in the horizontal plane is required for human depth perception (Howard, 2012; Jainta et al., 2015). The roles of vergence and binocular disparity have also been studied during the viewing of illusions (e.g., Logvinenko, Epelboim, & Steinman, 2001). Horizontal vergence movements (i.e., convergence and divergence) might also contribute to this process, by aligning binocular coordination with retinal image disparity, in response to near and far stimuli (cf. Cornell et al., 2003). Cornell et al. (2003) explored binocular eye movement with three angles of vergence change under near and far conditions. They found that the eyes behave differently in response to near and far viewing conditions, with under-convergence from near fixations and over-convergence for far fixations. This indicates a possible change of eye-movement behaviours to adapt to far and near objects under natural viewing conditions. Therefore, in **chapter 7** we will explore the potential adaptation of binocular behaviours in response to the same experimental stimuli with two spheres with vergence movements.

1.6.2 Visual illusion

Motion perception and illusion have gained a lot of interest from psychologists in recent decades. Researchers have found that human vision is sensitive to the direction of motion, with a

response in retinotopic cortex based on motion-sensitive neurons (Raemaekers et al., 2009). Sensitivity of human perception to motion shows specificity to particular types of visual stimuli as well as to directionality (Fahle & Wehrhahn, 1991; Naito et al., 2010; Raemaekers et al., 2009). Previous research on specific visual motion processing such rotating black and white spiral spirals as (Scott et al., 1966; Takeuchi, 1997) drew attention mostly to the motion aftereffect (Anstis et al., 1998; Huk et al., 2001; Mather et al., 1998; Wohlgenuth, 1911) and the difference in visual sensitivity towards these stimuli. Some researchers have found that anticlockwise spirals elicit more visual effort to process than the clockwise spirals (Scott, Lavender, McWhirt, & Powell, 1966; Lewis & McBeath, 2004; Edwards & Badcock, 1993; Lages et al., 2009), whereas others report greater sensitivity in response to clockwise spirals (Giaschi et al., 2007; Raymond, 1994). Lages et al. (2017) also report improved visual acuity due to the anticlockwise spiral motion aftereffect.

Researchers have proposed that prolonged exposure to visual stimuli having a particular motion and orientation could potentially lead to aftereffects through adaptive visual coding in the neural system (Wainwright, 1999). Clifford (2002) further explained that the underlying process of adaptation to orientation and motion, would facilitate and optimize the dynamic use of a range of visual pathways by matching visual stimulation. These all indicate a significant process of the visual system adapting to visual stimuli in terms of the perception of orientation and direction of the motion to produce a motion aftereffect, from a cortical perspective. But what would be the psychophysical implications of these specific type of stimuli for the visual system?

In **chapter 8**, we further explore the process of adaptation of visual system in response to illusional motion processing, specifically when viewing a visually challenging stimulus, Plateau's Spiral (Wade & Heller, 2003). How would the two eyes respond to stimuli that produce a motion-

based illusion, given that such stimuli produce not just an aftereffect but different perceptions *during* the stimulus? We will investigate the adaptation and adjustment of the visual system during visual motion processing, in terms of hemispherical projection and the coordination of binocularity.

1.6.3 Contrast change

The visual system continuously adapts to luminance, colour, motion and contrast (e.g., Ghosh, Zheleznyak, Barbot, Jung, & Yoon, 2017; Kirkby, Blythe, Drieghe, Benson & Liversedge, 2013; Schaeffel, 2017). It has been widely perceived that the human visual system can adapt to contrast according to the detected sensitivity to contrast (Blakemore & Campbell, 1969; Baccus & Meister, 2004). The sensitivity and behaviour of visual functions in response to contrast in reading and non-reading tasks has been studied by researchers for many years (Legge, Rubin, & Luebker, 1987; Schiller et al., 1990; Legge, Ahn, Klitz, & Luebker, 1997; Nasanen et al., 2001; Reingold & Rayner, 2006; Mace et al., 2007; Fujita et al., 2008; Jasky et al., 2011; Glaholt, Rayner, & Reingold, 2014; Schaeffel, 2017). This ability to distinguish between light and dark stimuli with no clear boundaries is defined as contrast sensitivity (Ginsburg, 2003). It has been argued that decreasing text-background contrast would cause increasing reading difficulty (Shillcock et al., 2010) and thus affect visual performance (Fujita et al., 2008). It has also been claimed that visual behaviours are not influenced by the characteristic of positive or negative polarity context (Buchner & Baumgartner, 2007; Buchner et al., 2009).

The influence of reduction of contrast on reading performance also has been investigated in eye movement behaviour, with increased numbers of fixations and fixation durations (Legge, Parish, Luebker, & Wurm, 1990; Johansson, Pansell, Ygge, & Seimyr, 2014) as well as shrinking of the visual span (Legge et al., 1997). In addition, Abbonizio et al. (2002) has reported a

significant enhancement effect for contrast discrimination under binocular conditions when viewing at low levels of contrast. This enhancement has been further suggested to be an adaptive behaviour via binocular change (Meese et al., 2006).

All these behaviours may affect the efficiency of binocular viewing in response to local contrast. According to Jainta et al. (2017), binocular processing behaviours are generally related to binocular summation, where more robust visual information is received from the combined signals of the two eyes' receptors, facilitating detection and discrimination of visual stimuli (Blake, Sloane, & Fox, 1981; Blake & Wilson, 2011). During this process, visual information such as luminance and contrast would be extracted in early visual processing. In addition, it has been reported that change of contrast results in a change of vergence signals (Abbonizio et al., 2002). Johansson et al. (2014) reported changing performance in reading speed and fixation duration according to the level of contrast. They concluded that the efficiency of binocular processing is influenced by the degree of contrast. This also means the variation of text-background contrast elicits more specificity for adaptation via binocular vision.

Similar findings have been shown in reading and non-reading tasks in binocular processing. Kirkby et al. (2010) has reported a quite similar magnitude of fixation disparity in reading non-linguistic stimuli, compared with results in reading research (Liversedge, Rayner, et al., 2006), despite differences of experimental settings such as font size or viewing distance. This result is consistent with the previous literature exploring the task-specific modulation of binocular behaviours (Bucci & Kapoula, 2006; Blythe et al., 2006; Roufs & Boschman, 1997). Similar binocular modulation has also been reported in digit reading in response to contrast reduction, showing increased fixation duration and saccade amplitudes and decreased visual span (Nasanen et al., 2001). These reports all suggest potential universal behaviours in response to variation of

contrast regardless of reading linguistic or non-linguistic stimuli. How would contrast influence eye movements in reading specifically? We will investigate this further in **chapter 5** to understand how the visual system reacts and adapts to continuous text-background contrast in by exploring the disparity-related eye movement behaviours in a reading-like task.

1.6.4 Blur adaptation

Our vision system continuously adapts and changes its responding to features based on viewing experience. Blurry displays reduce the contrast of the information (Walsh & Charman, 1989) as well as increasing perceived relative distance (O'Shea et al., 1997; Lewis & Maler, 2002). The human visual system has been reported to adapt and accommodate to the blurriness of object by learning to appreciate the degree of blur in the stimuli; the effect is strong in familiar objects (Howard, 2012). The perceived object blurriness would be transmitted to the visual cortex and related areas and the cells in these areas respond to the changes in the blurriness of the stimulus as well as the changes in binocular disparity (Howard, 2012). This indicates that the binocular system would correspond to a signal of blurriness of perceived information.

How would the two eyes' fixation points correspond to blurry information specifically? Shillcock et al. (2010) have argued that conjoint foveation may not always happen and is not always necessary in binocular nonreading tasks. Jaschinski-Kruza (1994) reported the strong influence of blur on binocular behaviours, resulting in great exophoric vergence change when reading blurred stimuli. Kasthurirangan et al. (2003) has quantified accommodative behaviour of amplitude when viewing blurred stimuli and Bharadwaj and Schor (2005) further describe this blur-driven accommodation.

Suryakumar et al. (2007) and Jainta et al. (2011) found that though performance of text comprehension was not changed when reading blurred text, the vergence of binocular fixations was adjusted compared with reading normal texts, indicating potential accommodating behaviours. Jainta et al. (2011) found that the tendency of an exo shift increased, induced by blurring reading targets and consistent with previous findings (Jaschinski-Kruza, 1994), however, they attributed this change of binocular coordination in reading blurry text to the development of fatigue and visual strain. **In Chapter 6**, we will further investigate binocular behaviours in responding to blurriness of perceived information and how the visual system adapts to blurred stimuli by accommodating visual movements accordingly.

1.7 Eye-tracking research, measurement and issues

Eye-tracking as a research tool is used to record eye-movements (Holmqvist et al., 2011). Some of the more commonly used eye-trackers in Psychology are the Eye-link series eye-trackers from SR-Forum and the Dual Purkinje Image (DPI) eye-tracker from Fourward Technologies. The DPI eye trackers use the fact of the structure of the eyes reflecting objects in the real world with Purkinje images, whereas Eyelink technology adopts video-based reflection from the cornea and the pupil which also supplement the use of DPI technology (Bao, 2019). Questions have been raised to discuss the reliability on certain technologies and their algorithms and potential issues caused by it, especially on the measure and the data quality of the trackers (Nyström & Holmqvist, 2010; Holmqvist et al., 2012; Hooge et al., 2019).

Researchers show concerns about details of eye movement features (Hooge et al., 2016). They have reported the Post Saccadic Offset (PSO) by studying the algorithm and relevant signals (Nyström et al., 2013b; Nyström et al., 2015). It has been argued that PSO of the lens from DPI trackers is partly captured by the term dynamic overshoot slightly (Bao, 2019). Several studies

have also focused on the PSO of the pupil in the data subtracted from Eyelink trackers. Nyström et al. (2013b) argued for the potential influence of the PSO of the pupil on unstable eye position. Their research team further report a nonsignificant effect of the lens and a possible cause of the individual shape of the PSO for event detection (Nyström et al., 2015; Hessels et al., 2018).

In addition, data were recorded every 2ms on pupil size and corneal reflection in the Eyelink II and Eyelink 1000 trackers which show relatively more moderation for measurements. All participants would be calibrated to align their fixating location based on the calculation of the algorithm. Nyström et al. (2013a) show that monocular calibration and background synchrony of the task and calibration support the best data quality.

1.8 Questions

In the light of this review of the literature, I explore the following questions.

What is the division of labour between the two eyes in reading?

Is it the same in English and Chinese? Is it the same for right-to-left languages?

What happens when reading happens in visually very adverse conditions?

Does this division of labour reflect the specialisms of the cerebral hemispheres?

Does the behaviour of the eyes show an influence of higher cognition?

Below, we investigate binocular strategies in visual perception in response to different stimuli and conditions in both reading and non-reading tasks, to further our understanding from peripheral binocular movement all the way to higher cognitive processing.

Chapter 2

Methodology

In this chapter, the methodology for all the experiment would be explained in detail, including both reading and non-reading sections.

2.1 Reading experiments

2.1.1 Participants

We paid 36 Chinese, 38 English, 28 Arabic and 16 Hebrew native speakers for their participation. All tested and reported as having normal or corrected-to-normal vision. They were students at the University of Edinburgh. The Chinese, Hebrew and Arabic participants all had English as a second language. The English participants had a variety of exposures to other languages.

2.1.2 Apparatus

Participants sat in a room with diffused lighting, and watched a 22" Iiyama Vision Master Pro 514 display, at a distance of 75 cm. The screen resolution was 1024 x 768 pixels. A chin-rest and forehead support kept the head stable. The eye-tracker was an SR Research EyeLink II head-mounted video-based tracker.

2.1.3 Stimulus Materials and Procedure

We recorded eye movements binocularly, using the EyeLink II's pupil tracking and corneal reflection, and sampled at 500Hz (i.e. every 2 msec), during the reading of English (24 pt monospaced Monaco font), Chinese (PMingLiU, standard print), Arabic (al naskh font) and

Hebrew (Miriam font) texts, each comprising 21 newspaper stories , with a total of 5000 words for each language, presented in black characters on a light background, on consecutive pages with up to five justified lines of text each. The text was left or right justified based on the starting line of the orthographies; note that the nature of Chinese orthography means that line length is much more regular for Chinese, compared with a ragged right edge for English, meaning that English lines were on average shorter.

The stimuli were intended to be comparable in form and content between the five languages in the overall study (English, Chinese, Arabic, Hebrew, Spanish), based on the intuitions of native speakers. The maximum line length corresponded to 64 English characters. Readers were calibrated monocularly with a 9-point fixation grid while occluding the other eye with a black paper shade. Participants fixated a black fixation disc before each page of text was displayed and fixated a square at the bottom right of each page after finishing reading it. They responded on the keyboard to a yes/no question after each story, to ensure reading for meaning.

Mean comprehension accuracy was 77%, 82%, 90.5% and 90.8% for English, Chinese, Arabic and Hebrew respectively, indicating that participants read for meaning; no data were excluded on this criterion. The grid of fixation targets was presented before the next article, to check the calibration accuracy. The whole recording process consisted of three blocks with intervening rest-breaks, lasting for around 1.5 hours in total.

2.2 Non-reading experiments

2.2.1 Participants

We paid 38 males whose first language was read from left to right to participate. They all reported having normal or corrected-to-normal vision.

Demographic information:

- Age: all between 19-30 and students from the University of Edinburgh.
- First language: 12 with English, 11 with Chinese, 4 with Spanish, 3 with German, 2 with Italian, 2 with Dutch, 1 with Tamil, 1 with Polish, 1 with French, 1 with Swedish.
- Dominant eye: 14 people with left eye, 24 people with right eye.
- Handed(L/R): 11 are left-handed, 27 are right-handed.

2.2.2 Apparatus

Participants sat in a room with diffused lighting, and watched a 22" Samsung SyncMaster 2233 display, at a distance of 74 cm. The screen resolution was 1068 x 1050 pixels at 60Hz. A chin-rest and forehead support kept the head stable. The eye-tracker was an SR Research EyeLink 1000 video-based tracker.

2.2.3 Stimulus materials and procedure

Eye movements were recorded binocularly in desktop mode with pupil and corneal reflection and sampled at 550Hz. Participants were calibrated monocularly with a 9-point fixation grid while occluding the other eye with a black paper shade before each block of the experiment. The calibration background was the average perceived colour of the task stimuli (cf. Nystrom et al., 2012). Each participant was tested individually. Participants were informed that there would be a simple visual reading task and they would be experiencing visual stimuli on the display screen, that they should follow the instructions on the screen and press the key to continue the task at their own pace. The experiment was designed in Experiment Builder (developed by SR-Forum). The order of the experiment is fixed for all participants, with spiral set 1, spheres, spiral set 2, faded, spiral set 3, faint, spiral set 4. The experiment lasted for approximately 1 hour.



Figure 2.1 *Sample stimulus.*

2.2.3.1 Experiment with Faded stimuli

After a successful calibration (average calibration error less than .5), the participant read out loud the line of numbers one by one as accurately as possible. Each display had 54 white random numbers (font size 14) across the middle of the screen (Figure 2.1). The background colour gradually faded from pure black to pure white, from left to right across the screen, created with Photoshop's fading function, making the numbers increasingly difficult to read. There were two blocks of 10 trials with an intervening rest-break. Participants pressed any key for the next stimulus when they could not recognize any more numbers. There was a second calibration before the second block.

2.2.3.2 Experiment with Faint stimuli

After a successful calibration (average calibration error less than .5), the participant was instructed to read out loud the line of numbers one by one and try their best to recognize as many as possible. Each display had 54 numbers and appeared in black, ranging from 0 to 9, font size 14 (Figure 2.2). The numbers were processed by Photoshop to look more and more faint from the left to the right of the screen. A line of numbers was divided equally into four sections; in each section, the numbers were selected and blurred with the built-up function in Adobe Photoshop software. The section was selected with Marquee tool and then use the blur function. Each section was operated and blurred separately with different levels of blurriness (Mode normal and Strength with 25%, 50%, 75% and 100%) based on the blur tool in PS, from the left to the right. Thus, the numbers got harder and harder to read due to the gradual decreasing sharpness. There were 10 displays in each block and participants could press any key to progress when they could not recognize any more. The whole recording process consisted of two blocks of 10 trials with an intervening rest-break, with a calibration before each block.



Figure 2.2 Sample stimulus as seen on the screen.

2.2.3.3 Experiment with Spheres

After a successful calibration (average calibration error less than .5), the participant was instructed to follow the green dot on the sphere and fixate it. There were two types of tasks and they consisted of 2 blocks*10 trial and 1 block*4 trials for task 1 and 2 respectively, with intervening rest-breaks.

The sphere stimuli were the same as in Murray, Boyaci & Kersten (2006). There were two spheres, one at the ‘front’ and one at the ‘back’; both were the same physical size but appear to be a different perceptual size due to the background. Details can be seen in Figure 6.1 and Figure 6.2 of Murray et al. (2006) (see Fig. 2.3 and 2.4, below).

There were two types of tasks.

Sphere 1 task

In the first task, participants viewed just the front sphere or just back sphere alternately, with the green dot appearing at the centre of the sphere to guide where to fixate before the actual sphere appeared (see Fig. 2.3). The front sphere always appeared first. The green dot showed for 0.8s and was followed by the sphere showing for 2s. There was a practice trial before the experimental blocks, consisting of three trials. Each block contained 10 trials (front & back) and there were two blocks, with recalibrations between each block.

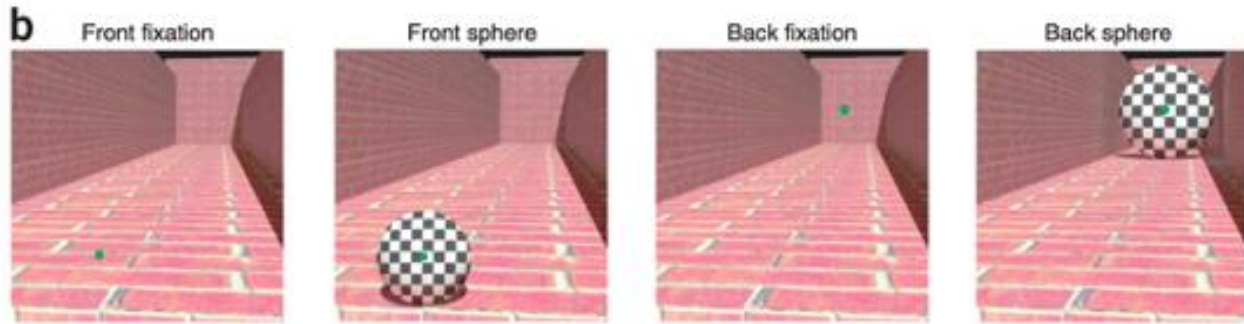


Figure 2.3 *The stimuli for the Sphere 1 task.*

The task shows from the left to the right in the figure above suggests. The green dot appears ahead of the sphere in each position.

Sphere 2 task

In the second task, both front and back spheres appeared on the same screen (see Fig. 2.4) and the participant was instructed to fixate the front and back spheres alternately as fast as possible, with the green dot to guide the position of fixation. Each session lasted for 30s and there were four sessions in total in this task.

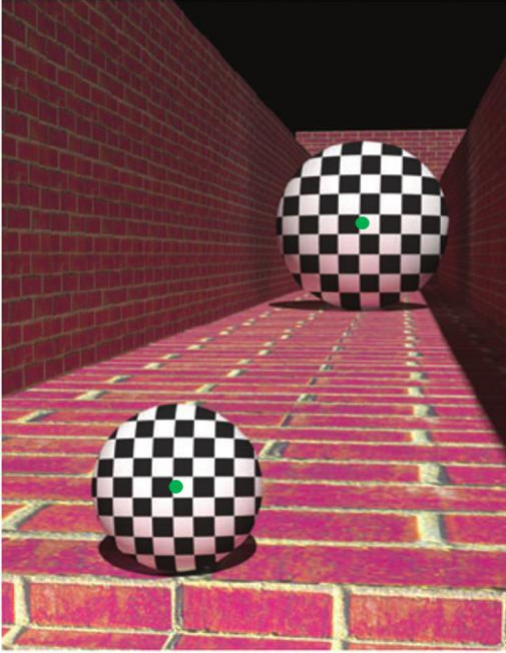


Figure 2.4 *The stimulus for the Sphere 2 task. Both spheres appear at the same time and the participants are instructed to fix at the green dots.*

2.2.3.3 Experiment with Spirals

After a successful calibration (average calibration error less than .5), the participant was instructed to fixate at the centre of the screen and the spiral video was centred in the screen. There were two types of spiral movement, clockwise and anti-clockwise. Each spiral had the same speed of rotation and lasted for 30s and was repeated four times respectively in the whole experiment. The first spiral ('clockwise') appeared, then there was a 30s compulsory break time to rest the eyes from the aftereffect. After 30s, participants could press the key to continue anytime they wanted, to progress to the next spiral ('anticlockwise'). The two types of videos being watched were set as one task divided into four sets and separated in time by other tasks not part of this experiment. The order of presentation of clockwise and anticlockwise were not counterbalanced; clockwise always preceded anti-clockwise, in this first exploration of eye-movements during the watching of the spiral illusion. Figures 2.5 and 2.6 show the stimulus with clockwise and anticlockwise spirals

respectively. The whole recording process consisted of four blocks and each block includes clockwise and then anti-clockwise spirals as a set.

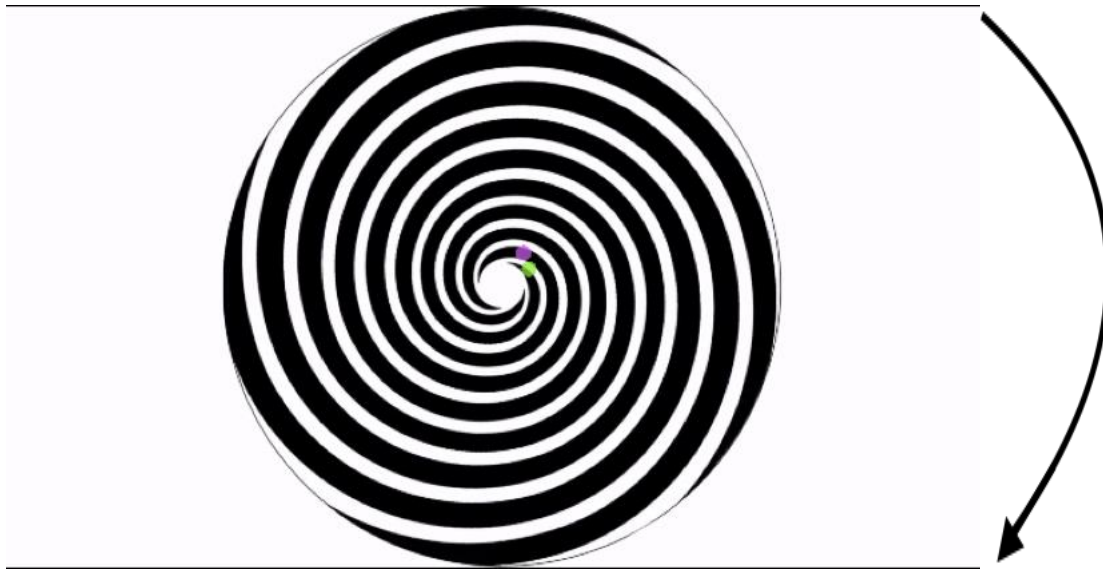


Figure 2.5 Two eyes fixate at the Clockwise spiral (pink dot as left eye and green dot as right eye)

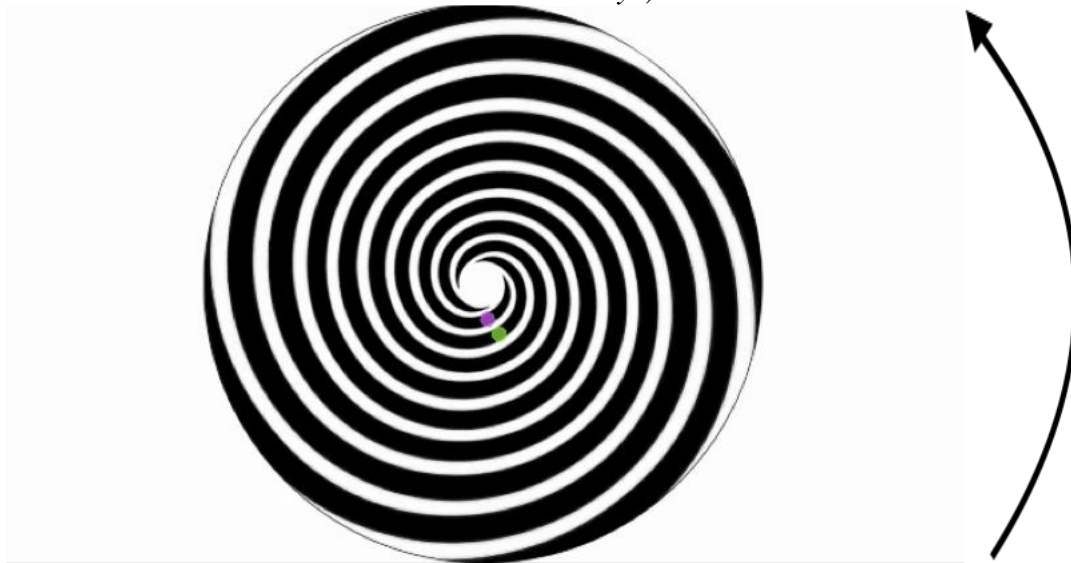


Figure 2.6 Two eyes fixate at the Anticlockwise spiral (pink dot as left eye and green dot as right eye)

Chapter 3

Synchrony and asynchrony in binocular fixations in the reading of English and Chinese; the implications for ocular prevalence

Abstract

In this chapter, we investigated small temporal non-alignments between the two eyes' fixations in the reading of English and Chinese. We define nine different patterns of asynchrony and report their spatial distribution across the screen of text. We interpret them in terms of their implications for ocular prevalence—prioritizing the input from one eye over the input from the other eye in higher perception/cognition, even when binocular fusion has occurred. The data are strikingly similar across the two very different orthographies. Asynchronies in which one eye begins the fixation earlier and/or ends it later occur most frequently in the hemifield corresponding to that eye. We propose that such small asynchronies cue higher processing to prioritize the input from that eye, during and after binocular fusion.

3.1 Introduction

How much is language-specific, how much is universal? We assume that readers coordinate their eyes to optimize higher visual processing. In reading, binocular fusion is crucial to this process and must involve deciding how much higher visual processing should rely on the input specific to each eye. This 'ocular prevalence' has typically been discussed in terms of quantitatively resolving stereo-disparate images (cf. Kommerell, Schmitt, Kromeier, & Bach, 2003) but is a wider, subtler issue of combining similar inputs (Shillcock et al., 2010). How is this fluid division of labour between the eyes mediated?

Temporal disjugacy, the small-scale temporary unyoking of the two eyes' fixations in time, has been explored less than spatial disjugacy. Below we report binocular fixation data in reading English and Chinese in terms of small temporal asynchronies between the two eyes during multiline reading. We explore non-alignments in the timing of the start and end points of the fixation of the two eyes.

There are viewing conditions and visual tasks, such as sighting and pointing tasks, in which the viewer can only engage accurately with the real world by allowing one eye's input to dominate completely (Kommerell et al., 2003; Porac & Coren, 1976). Such ocular dominance is skewed towards the right eye, over the population (Hillemanns, 1927). The implications of ocular dominance are unclear; Mapp, Ono and Barbeito (2003) have claimed that the dominant eye may have "no unique functional role in vision" (p. 310).

However, there are more pervasive viewing conditions and tasks in which the inputs from the two eyes can be combined. The contradiction between the inputs from the two eyes gives rise to depth perception, essential in everyday tasks of fine manual control such as threading a needle. One eye's input can still be prioritized in the final conscious percept—ocular prevalence. Stereo-disparate images have primarily been used in the operational definition and exploration of ocular prevalence, in which Kommerell et al. (2003) find that the right and left eyes are equally likely to be preferred in different individuals. Crucially, Kromeier, Schmitt, Bach and Kommerell (2002) show that ocular prevalence is still compatible with high stereo acuity at small stereo disparities.

What we consider below is the class of differences between the inputs from the two eyes in which there is no resulting depth perception, because there is no such stereo-disparity in the text stimulus (cf. Shillcock et al., 2010). Instead, the differences between the two inputs may result from viewing angle, as when the two eyes fixate the left end of a line of text; the left eye will be

closer, the right eye's view is more skewed, for instance. The differences in input may also result from inherent anatomical differences, such as size and shape of the eyeball. These differences in inputs still present a computational challenge to fuse the inputs to best advantage and there is still scope for ocular prevalence (the “graded quantification of the balance between the eyes”—Kommerell et al., 2003, p. 1397) to improve the division of labour between the two eyes. Such a quantitative, graded difference in cortical activation has been reported for dominance (Rombouts, Barkhof, Sprenger, Valk, & Scheltens, 1996), at least partly grounded in anatomy and physiology.

Below, we are concerned with how the conditions for ocular prevalence may play out in sustained reading from a screen. We tested two hypotheses in this chapter:

Hypothesis (1) The left eye will tend to begin fixating earlier and stay fixating longer in the left visual field, and the right eye will be similarly prioritized in the right visual field, thereby facilitating the appropriate switching of ocular prevalence.

This hypothesis is based on our prediction of a division of labour between the two eyes. There are differences in the projection of each eye to the primary visual cortex, favouring contralateral projection from the eye nearest the hemifield (e.g., left eye and left visual field) (Toosy, Werring, Plant, Bullmore, Miller & Thompson, 2001) (see Discussion, below). For eye-specific effects involving spatial attention, see, for instance, McCourt, Garlinghouse & Butler (2001).

Hypothesis (2) A very similar pattern of binocular temporal asynchronies will be found even across the two very different orthographies of English and Chinese.

This null hypothesis is based on our review, above, of some of the claims regarding similar and different reading behaviours in Chinese and English. If we find crosslinguistic dissimilarities in timing asynchronies, this will imply that higher cognitive processing, perhaps specific to reading,

is involved. If we find very similar qualitative patterns, it will imply that peripheral, anatomically based processing underlies the timing asynchronies.

This research involved the analysis of an existing corpus of eye-tracking data, the Edinburgh 5-Language Corpus. Below, for completeness, I present the details of the acquisition of this corpus, before describing the analysis.

3.2 Analysis

For each binocular fixation, the start-time offset was calculated as the fixation start-time of the right eye minus the fixation start-time of the left eye. The end-time offset was calculated analogously. A difference of ± 2 ms between events in the two eyes was considered as simultaneous, given the sampling rate. StartTime offset or EndTime offset < 2 means the right eye starts or ends earlier than the left eye. StartTime offset or EndTime offset > 2 means the left eye starts or ends earlier than the right eye. More specific description of the binocular offset to understand the concept can be found in the Appendix.

Figure 3.1 as a diagram depicts the comprehensive typology of offsets. There are nine possible types of binocular fixation, with different patterns of start-time and end-time offsets. The line above suggests timeline of the right eye during the fixation while the line below indicates that in the left eye. For example, Type 1 shows both eyes starting fixation synchronously and the left eye fixating for longer. The asynchronies themselves varied between participants, but trellis graphs (see Figures 3.5 and 3.6) revealed a robustly similar qualitative pattern across participants. The asynchronies formed a long-tailed distribution beginning in single-digit numbers of milliseconds.

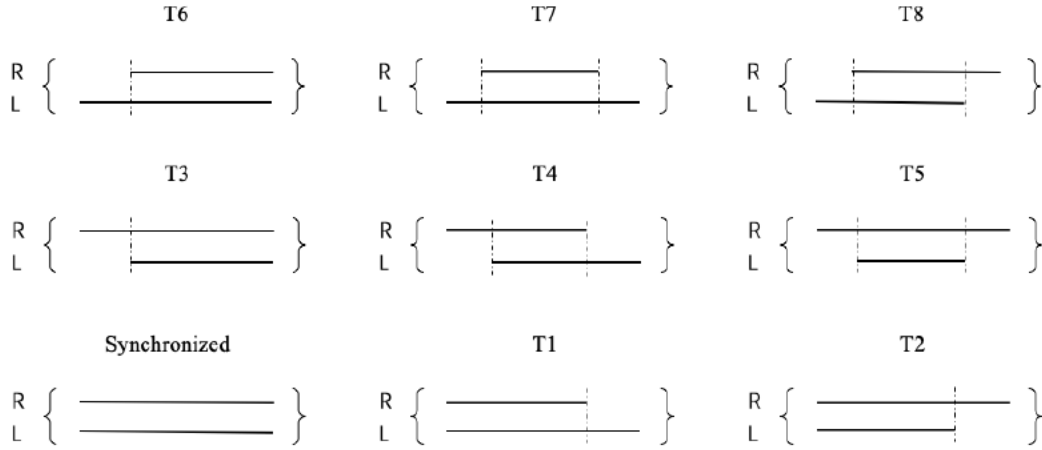


Figure 3.1 *Typology of binocular fixation asynchronies.*

Left-priority types: T1, T6, T7. Right-priority types: T2, T3, T5

In this chapter, we first produced demonstrative graphs to show the distributions of the types on the screen. We then analysed the data quantitatively with GLMER models, to further characterize the eye-movement behaviours and explore the potential implications for ocular prevalence.

3.3 Results

We analysed a total of 160,567 binocular fixations (i.e., pairs of individuals, temporally overlapping fixations by the left and right eye) for the English readers and 158,794 binocular fixations for the Chinese readers. Below, we first report descriptive statistics from two perspectives: (a) the overall distribution of the different types; (b) the spatial distribution of the types across the screen on which the text stimuli were displayed. Then, we report the quantitative analysis from GLMER models from two perspectives: (a) group (i.e., language, English and Chinese) differences; (b) screen differences under subsets of types (cf. Figure 3.1) in each group.

The results all together indicate a lawful patterning of binocular behaviours relevant to ocular prevalence, across the visual field.

3.3.1 Overall results

Figure 3.2 shows the overall distribution of each type and their percentages among all fixation pairs for English and Chinese readers respectively. Strikingly similar patterns obtain for both languages, with the three most numerous types of binocular fixation being the synchronized pairs, Type 3 and Type 6; in particular, synchronized binocular fixations account for over half the binocular fixations for both languages. Just over 80% of binocular fixations in both languages end synchronously.

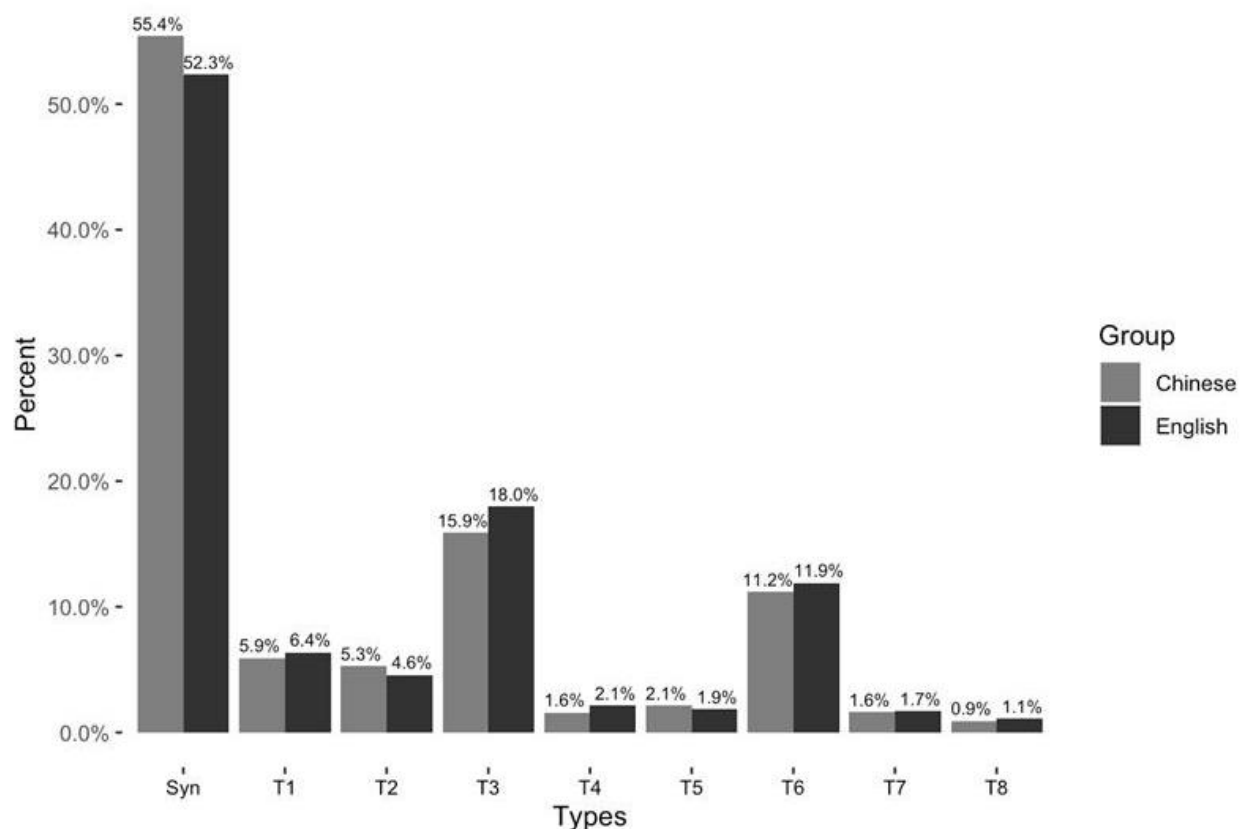


Figure 3.2 *The proportional distribution of types in English and Chinese readers.*

Syn, T3 and T6 are the main types in both groups.

3.3.2 Spatial distribution

Figure 3.3 shows the spatial distribution of each type on the lines of text, for English readers. The hexbin graph shows the mean coordinates (during the fixation) of the right eye for each binocular fixation, accurately representing the spatial distribution of binocular fixations (the choice of right eye over left has no implications here). The distributions reflect the fact that readers fixated a square at the bottom right of each page after reading it. The legend shows the frequency counts of fixations.

The fixation types Syn (synchronized), T3 and T6 show the greatest densities. There are clear differences between left, middle and end of each line. Syn fixations are concentrated most at the left of lines but span the whole line. T3 and T6 are skewed to the right and left of lines, respectively. T1 and T2 show slighter skewing to the left and right of lines, respectively. The remaining four types have less skewed distributions. The Chinese (Figure 3.4) and English data show qualitatively similar patterns. We divided the screen into left, middle and right, to investigate the implications for ocular prevalence, in the following analyses.

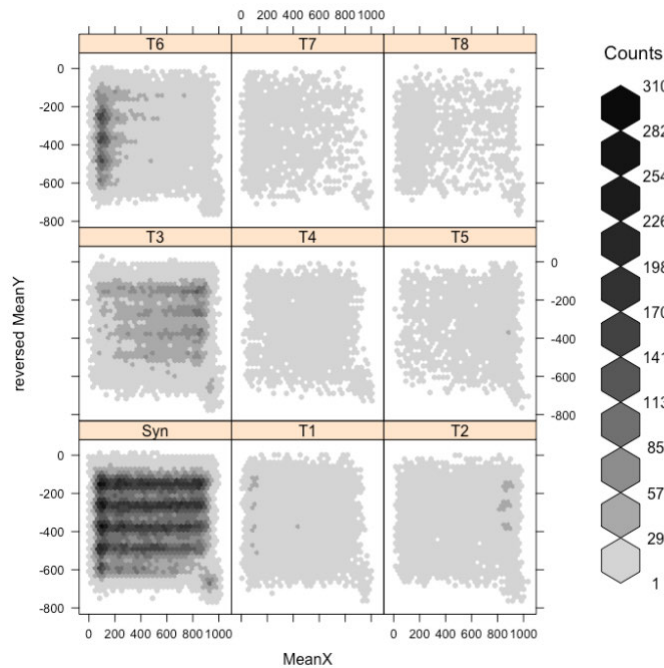


Figure 3.3 Spatial distribution of Types T1-T8 and synchronous fixations in English readers. T1, T6 and T7 (left prevalent) show concentration at the left side; T2, T3 and T5 at the right side.

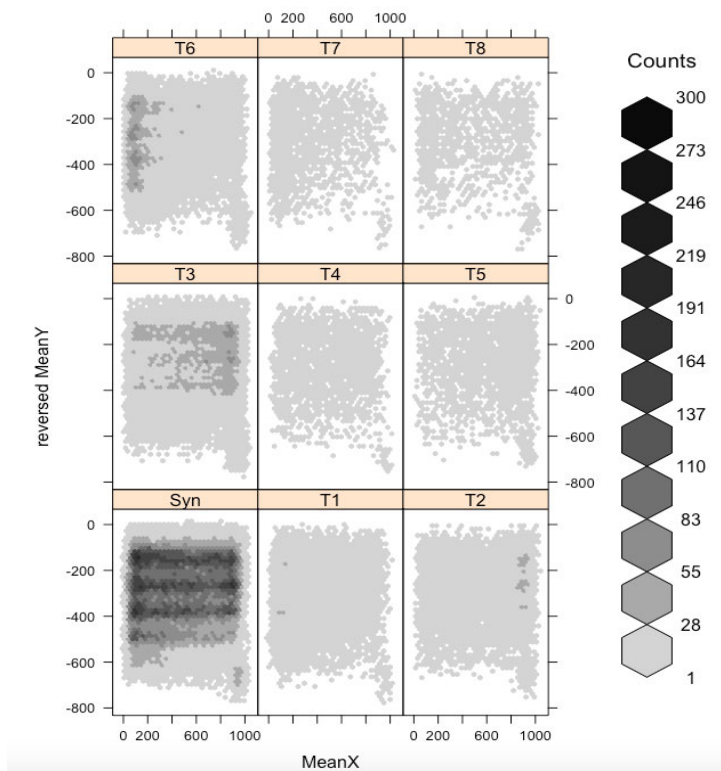


Figure 3.4 Spatial distribution of Types T1-T8 and synchronous fixations in Chinese readers. It shows similar trend as English readers.

3.3.3 Individual results

Figures 3.5 and 3.6 show the individual distribution of English and Chinese readers respectively. The individual type of distribution in all English data, as can be seen in Figure 3.5, shows most of the English readers follow the general type distribution, with the synchronized type predominating and followed by T3 and T6. Some readers stand out with higher synchronized fixations distribution than the others, such as 1, 12, 20 and 32 and 34. The individual distribution in Chinese data shows a very similar pattern. The percentage of synchronized pairs varies from 40% to 60% but mostly about 50%. While T3 varies from 20% to 40% and mainly around 20%, T6 changes from 10% to 20%, mostly around 10%. Nevertheless, some individuals still show different distributions. For example, 102 revealed a relatively balanced distribution among all types. This subject shows a relatively low synchronized rate in the vicinity of 30% and remarkable influence of T2 at around 20%.

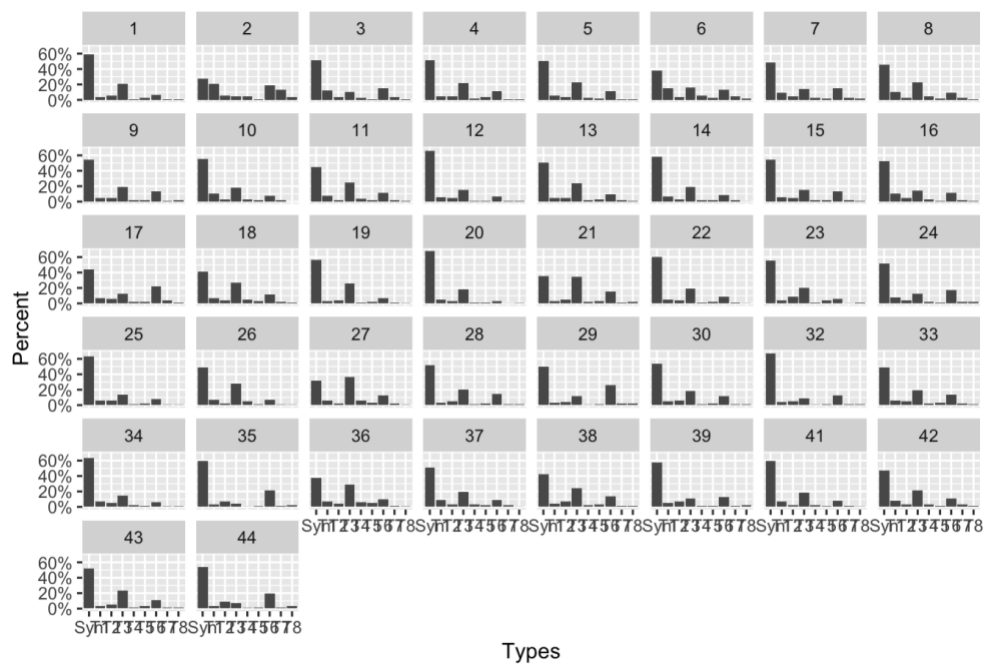


Figure 3.5 Individual distribution of Types T1-T8 and synchronous fixations in English readers

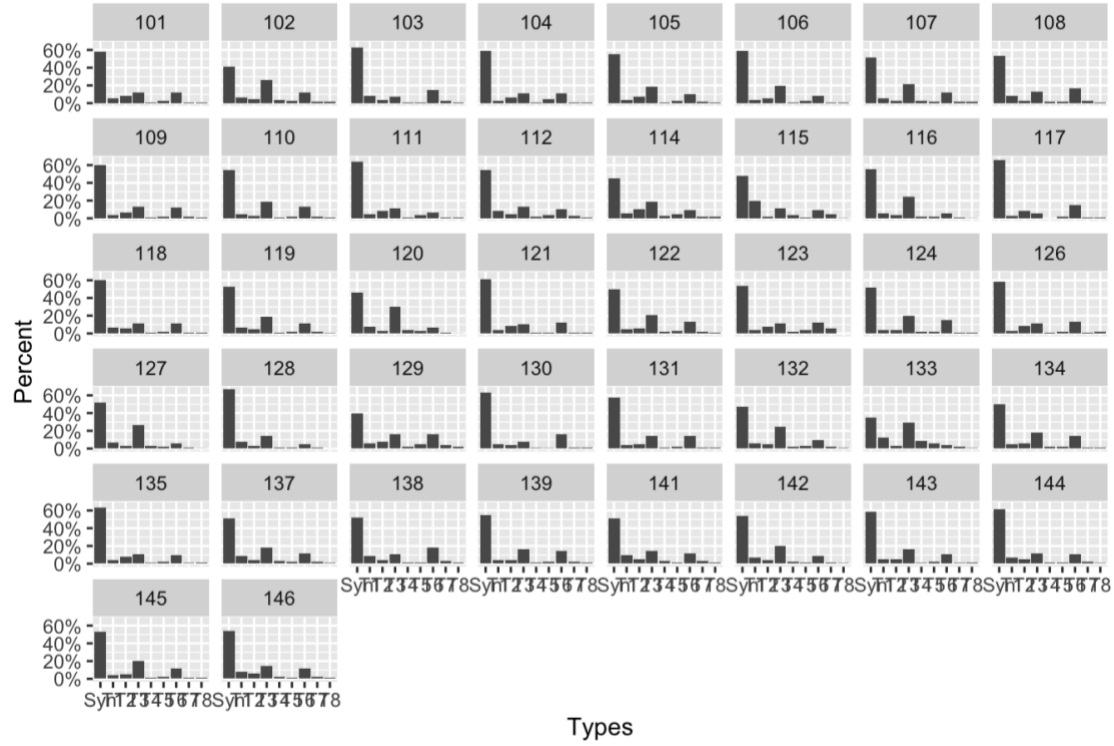


Figure 3.6 Individual distribution of Types T1-T8 and synchronous fixations in Chinese readers.

3.3.4 Modelling results

We use General Linear Mixed-Effects Regression Models (GLMER) in the following quantitative analyses, carried out in R using the lme4 software package (Bates, Maechler, & Dai, 2008). We used the counts of fixation pairs as dependent variables in all the models. As our dependent variable is counts of events, all our modelling used Poisson error distributions. We defined null models with participants, articles, page order (of each article) as random factors; we expected increased predictability through the successive pages of an article. Predictor variables included types (cf. Figure 3.1), groups (English, Chinese), the sides of the screen (left, middle and right, approximating left, middle and right of lines of text, middle as reference) and tested under subsets of types in each group separately to explore the quantitative distribution of the types. All Model fit was assessed using the anova function to compare models. The results show a systematic

pattern of binocular behaviour across languages, with the Chinese data being somewhat more systematic.

In the first part, we explored the interaction of all the types and sides of the screen altogether inclusively, in each Group. Then, in the second part, we explored our hypotheses within each Group separately (i.e., English and Chinese), with the main types. We explored the effects of synchronized fixations and T1, T2, T3, T5, T6 and T7 asynchronies within each language (i.e., counts of fixations for each comparison). (Types T4 and T8 were omitted from the analyses because their theoretical predictions were ambiguous.) In all these models, we added sides of the screen (left, middle, right; with the middle as reference) as a predictor variable to the null model.

GLMER analysis of Typology & Screenside in English

	The number of fixations sides of screen*types
Left	0.023 (0.004)
Right	-0.285 (<0.001)
TypeT1	-1.485 (<0.001)
TypeT2	-1.737 (<0.001)
TypeT3	-0.901 (<0.001)
TypeT4	-1.720 (<0.001)
TypeT5	-1.904 (<0.001)
TypeT6	-1.382 (<0.001)
TypeT7	-1.901 (<0.001)
TypeT8	-1.970 (<0.001)
Left:TypeT1	-0.027 (0.25)
Right:TypeT1	0.002 (0.956)
Left:TypeT2	-0.0003 (0.992)
Right:TypeT2	0.402 (<0.001)
Left:TypeT3	-0.407 (<0.001)
Right:TypeT3	0.309 (<0.001)
Left:TypeT4	-0.170 (<0.001)
Right:TypeT4	0.158 (<0.001)
Left:TypeT5	-0.055 (0.393)
Right:TypeT5	0.432 (<0.001)
Left:TypeT6	0.522 (<0.001)

Right:TypeT6	0.054 (0.046)
Left:TypeT7	0.135 (0.006)
Right:TypeT7	0.224 (0.006)
Left:TypeT8	0.081 (0.206)
Right:TypeT8	0.301 (<0.001)
Constant	1.959 (<0.001)
<hr/>	
Random effects	
	Variance
Participant(38)	0.0206
Article(21)	0.0019
Page(113)	0.0247
<hr/>	
Observations	50,007
Log Likelihood	-85,389.350
Akaike Inf. Crit.	170,838.700
Bayesian Inf. Crit.	171,103.300

Note: p value in parentheses.

Table 3.1 GLMER analysis of Screen differences in English all types

GLMER analysis of Typology & Screenside in Chinese

	The number of fixations sides of screen*types
Left	0.054 (<0.001)
Right	-0.143 (<0.001)
TypeT1	-1.637 (<0.001)
TypeT2	-1.760 (<0.001)
TypeT3	-1.124 (<0.001)
TypeT4	-1.953 (<0.001)
TypeT5	-2.019 (<0.001)
TypeT6	-1.490 (<0.001)
TypeT7	-2.052 (<0.001)
TypeT8	-2.115 (<0.001)
Left:TypeT1	0.055 (0.027)
Right:TypeT1	-0.031 (0.304)
Left:TypeT2	-0.125 (<0.001)
Right:TypeT2	0.348 (<0.001)
Left:TypeT3	-0.199 (<0.001)
Right:TypeT3	0.253 (<0.001)
Left:TypeT4	-0.116 (0.019)
Right:TypeT4	0.095* (0.068)
Left:TypeT5	-0.055 (0.347)
Right:TypeT5	0.339 (<0.001)
Left:TypeT6	0.411 (<0.001)

Right:TypeT6	0.005 (0.835)
Left:TypeT7	0.121 (0.020)
Right:TypeT7	0.085 (0.262)
Left:TypeT8	0.042 (0.548)
Right:TypeT8	0.203 (0.006)
Constant	2.048 (<0.001)
<hr/>	
Random effects	
	Variance
Participant(36)	0.0384
Article(21)	0.0037
Page(103)	0.0276
<hr/>	
Observations	45,480
Log Likelihood	-80,354.030
Akaike Inf. Crit.	160,768.100
Bayesian Inf. Crit.	161,029.800

Note: p value in parentheses.

Table 3.2 GLMER analysis of Screen differences in Chinese all types

GLMER analysis of screen difference in English T1

	The number of fixations	
	null model	sides of screen
	(1)	(2)
Left		-0.001 (0.962)
Right		-0.276 (<0.001)
Constant	0.407 (<0.001)	0.457 (<0.001)
<hr/>		
Random effects		
	Variance	Std.Dev.
Participant(38)	0.0257	0.1603
Observations	6,168	6,168
Log Likelihood	-8,252.810	-8,198.181
Akaike Inf. Crit.	16,513.620	16,408.360
Bayesian Inf. Crit.	16,540.530	16,448.720

GLMER analysis of screen difference in English T6

	The number of fixations	
	null model	sides of screen
	(1)	(2)
Left		0.586 (<0.001)
Right		-0.220 (<0.001)
Constant	0.810 (<0.001)	0.494 (<0.001)
<hr/>		
Random effects		
	Variance	Std.Dev.
Participant(38)	0.0713	0.2671
Article(21)	0.0012	0.0357

Page(113)	0.0127	0.1128
Observations	7,586	7,586
Log Likelihood	-13,332.040	-12,347.870
Akaike Inf. Crit.	26,672.080	24,707.740
Bayesian Inf. Crit.	26,699.810	24,749.340

Note: p value in parentheses.

Table 3.3 GLMER analysis of Screen differences in English T1 & T6 (both LE prevalent)

GLMER analysis of screen difference in Chinese T1

	The number of fixations null model (1)	sides of screen (2)
Left		0.122 (<0.001)
Right		-0.195 (<0.001)
Constant	0.423 (<0.001)	0.409 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(36)	0.0408	0.2020
Article(21)	0.0022	0.0475
Page(103)	0.0082	0.0906
Observations	5,571	5,571
Log Likelihood	-7,703.130	-7,638.904
Akaike Inf. Crit.	15,414.260	15,289.810
Bayesian Inf. Crit.	15,440.760	15,329.560

Note: p value in parentheses.

GLMER analysis of screen difference in Chinese T6

	The number of fixations null model (1)	sides of screen (2)
Left		0.462 (<0.001)
Right		-0.132 (<0.001)
Constant	0.775 (<0.001)	0.561 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(36)	0.0526	0.2295
Article(21)	0.0069	0.0832
Page(103)	0.0180	0.1345
Observations	7,283	7,283
Log Likelihood	-12,469.160	-11,906.030

Akaike Inf. Crit.	24,946.320	23,824.060
Bayesian Inf. Crit.	24,973.890	23,865.420

Note: p value in parentheses.

Table 3.4 GLMER analysis of Screen differences in Chinese T1 & T6 (both LE prevalent)

GLMER analysis of screen difference in English T2

	The number of fixations	
	null model (1)	sides of screen (2)
Left		0.023 (0.485)
Right		0.117 (<0.001)
Constant	0.312 (<0.001)	0.249 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	0.0134	0.1157
Observations	5,089	5,089
Log Likelihood	-6,390.994	-6,381.292
Akaike Inf. Crit.	12,785.990	12,770.580
Bayesian Inf. Crit.	12,799.060	12,796.720

Note: p value in parentheses.

GLMER analysis of screen difference in English T3

	The number of fixations	
	null model (1)	sides of screen (2)
Left		-0.377 (<0.001)
Right		0.027 (0.0443)
Constant	0.924 (<0.001)	1.013 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	0.0682	0.2612
Article(21)	0.0010	0.0330
Page(113)	0.0210	0.1450
Observations	10,317	10,317
Log Likelihood	-18,304.070	-17,903.600
Akaike Inf. Crit.	36,616.140	35,819.200
Bayesian Inf. Crit.	36,645.110	35,862.650

Note: p value in brackets.

Table 3.5 GLMER analysis of Screen differences in English T2 & T3 (both RE prevalent)

GLMER analysis of screen difference in Chinese T2

The number of fixations

	null model (1)	sides of screen (2)
Left		-0.071 (0.0248)
Right		0.205 (<0.001)
Constant	0.412 (<0.001)	0.324 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(36)	0.0347	0.1864
Article(21)	0.0028	0.0530
Page(103)	0.0031	0.0561
Observations	5,153	5,153
Log Likelihood	-7,074.346	-7,015.018
Akaike Inf. Crit.	14,156.690	14,042.040
Bayesian Inf. Crit.	14,182.880	14,081.320

Note: p value in parentheses.

GLMER analysis of screen difference in Chinese T3

The number of fixations		
	null model (1)	sides of screen (2)
Left		-0.133 (<0.001)
Right		0.125 (<0.001)
Constant	0.899 (<0.001)	0.887 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(36)	0.0728	0.2699
Article(21)	0.0028	0.0529
Page(103)	0.0283	0.1684
Observations	8,963	8,963
Log Likelihood	-15,850.500	-15,722.270
Akaike Inf. Crit.	31,708.990	31,456.550
Bayesian Inf. Crit.	31,737.400	31,499.150

Note: p value in parentheses.

Table 3.6 *GLMER analysis of Screen differences in Chinese T2 & T3 (both RE prevalent)*

The majority of the non-Syn types—T1, T2, T3 and T6—are similarly distributed in both groups. The patterns suggest ocular prevalence. First, Table 3.1 and 3.2 both imply left-eye priority at the left side and right-eye priority at the right side. Then, the separate models support the indication. Table 3.3 shows that T1 and T6 (left-eye priority) have significantly less value on the right side of the screen compared with the middle (i.e., the reference) in English readers. T6 also

has significantly more value on the left side. Similar results can be observed in Chinese readers (Table 3.4), particularly in T6; additionally, Chinese T1 has significantly more value on the left side.

Furthermore, Table 3.5 shows T2 and T3 (right-eye priority) having significantly more value on the right side of the screen in English readers, and T3 having significantly less value on the left side. Finally, Table 3.6 shows Chinese T2 and T3 have more value on the right side and significantly less value on the left side of the screen.

GLMER analysis of screen difference in English T5

	The number of fixations	
	null model	sides of screen
	(1)	(2)
Left		-0.038 (0.547)
Right		0.111 (0.0164)
Constant	0.198 (<0.001)	0.135 (<0.001)
Observations	2,350	2,350
Log Likelihood	-2,701.678	-2,696.226
Akaike Inf. Crit.	5,407.357	5,400.452
Bayesian Inf. Crit.	5,418.881	5,423.501

Note: p value in parentheses. All random intercepts were equal to zero

GLMER analysis of screen difference in Chinese T5

	The number of fixations	
	null model	sides of screen
	(1)	(2)
Left		0.018 (0.749)
Right		0.147 (0.001)
Constant	0.243 (<0.001)	0.153 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant (36)	0.0037	0.0615
Observations	2,336	2,336
Log Likelihood	-2,784.874	-2,777.907
Akaike Inf. Crit.	5,573.748	5,563.813
Bayesian Inf. Crit.	5,585.260	5,586.838

Note: p value in parentheses.

Table 3.7 GLMER analysis of Screen differences in English & Chinese T5 (RE prevalent)

This systematic binocular pattern is further seen in T5 (right-eye priority) and T7 (left-eye priority) in both orthographies, though the data are relatively sparse. We find significantly more value at the right side compared with the middle in both English and Chinese T5 (Table 3.7). Results also show significantly more value at the left side compared with the middle in T7 in both orthographies (Table 3.8). In addition, the results of English T4 (early-right and late-left priority) shows a significant concentration in the middle with significantly less at the left side (Est= -0.1269, SE= 0.0427, $z(2700) = -2.972$, $p < .01$) as well as the right side (Est= -0.1141, SE= 0.0422, $z(2700) = -2.703$, $p < .01$).

GLMER analysis of screen difference in English T7

	The number of fixations	
	null model	sides of screen
	(1)	(2)
Left		0.142 (0.003)
Right		-0.071 (0.370)
Constant	0.194 (<0.001)	0.110 (0.007)
Random effects		
	Variance	Std.Dev.
Participant(38)	<0.0001	<0.0001
Observations	1,962	1,962
Log Likelihood	-2,248.452	-2,241.014
Akaike Inf. Crit.	4,500.904	4,490.028
Bayesian Inf. Crit.	4,512.067	4,512.355

Note: p value in parentheses.

GLMER analysis of screen difference in Chinese T7

	The number of fixations	
	null model	sides of screen
	(1)	(2)
Left		0.158 (0.002)
Right		-0.050 (0.505)
Constant	0.189 (<0.001)	0.094 (0.046)
Random effects		
	Variance	Std.Dev.
Participant(36)	0.0039	0.0631
Observations	1,869	1,869
Log Likelihood	-2,156.164	-2,148.010
Akaike Inf. Crit.	4,316.329	4,304.021
Bayesian Inf. Crit.	4,327.395	4,326.153

Note: p value in parentheses.

Table 3.8 *GLMER analysis of Screen differences in English & Chinese T7 (LE prevalent)*

3.4 Discussion

Overall, we have found that the distribution of small asynchronies of binocular fixation accord with ocular prevalence, in line with our prediction. When readers fixate towards the left of a line (and the left of peripersonal space), the left eye tends to be prioritized in starting and ending fixations. The converse happens for the right eye. Statistical modelling supports the visualization of the data seen in Figures 3.3 and 3.4. Again, in line with our prediction, we found strikingly similar qualitative patterns between the Chinese and English readers. This potential role for ocular prevalence confirms the increasing importance that reading researchers have given to binocular coordination of eye movements over the last two decades.

What is the fundamental advantage of such delicate switching of processing between the eyes? Why should we expect to see it? The visual pathways obey the neuroanatomical principle of contralateral projection. Thus, the left eye itself projects more strongly to the right hemisphere and the right eye to the left hemisphere (as well as contralateral projection *within* each eye), reflecting (a) the exclusively contralateral monocular crescent of the temporal hemifield of each eye, (b) the biased crossed projection of nasal retinal ganglion cells which drive the contralateral ocular dominance columns in V1, and (c) the blind spot representation in the ipsilateral visual cortex (Toosy et al., 2001). We should therefore expect the fluid reprioritizing of the input from either eye as the reader's gaze crosses the line, to facilitate visual and lexical processing (cf. Obregón & Shillcock, 2012).

Binocular fusion crucially facilitates visual processing (e.g., Blake & Fox, 1973; Jones & Lee, 1981; Ogle, 1964). Fusion is a process that occurs over time and may be affected by non-

conjugate fixational eye-movements (drift, nystagmus and microsaccades) (Otero-Millan, Macknik & Martinez-Conde, 2014), by the existence of spatial disparity between the fixation points of the two eyes (Liversedge et al., 2006) and by the directional details of any such disparity (Kim, Choi & Sohn, 2012). But fusion raises the question of which eye's input should have priority for higher, conscious processing, because there are necessarily always differences between the two inputs, whether because of the different lines of sight or the different physical parameters of the two eyes. In this sense, the exigencies of ocular prevalence pervade visual processing.

Switching prevalence within the binocular fusion of successive fixations thus becomes a central issue. The default solution seems to be that prevalence is given to the nearest eye to the target in peripersonal space; thus, in reading, the left eye tends to be prioritized at the left end of the line, the right eye at the right end of the line. We suggest that the physical constraints on the two eyes are intimately engaged in determining ocular prevalence. In the data we have explored, these physical constraints have involved the start and end time for the fixations of the two eyes. We suggest that these small timing differences assist and reflect ocular prevalence.

Both of the orthographies studied progress left-to-right. One way to understand the results is that in return sweeps from the end of one line to the beginning of the next, the left eye had tended to travel faster than the right eye and thus arrive earlier to start the fixation. Smaller, regressive (i.e., right-to-left) eye movements on the same line may be further candidates for this explanation; longer such regressions may provide more scope for a left eye priority, again tending to emphasise the beginning of the line. Such right-to-left movements involve the left eye's lateral rectus muscle, associated with faster acceleration (Robinson, 1964); the left eye gets there first.

The lateral rectus muscle is critical for *abductive* saccades—moving away from the nose. Its relative strength over the musculature controlling *adductive* saccades (towards the nose) means

that left-to-right movements across the line of text will tend to favour the abducting right eye, which will tend to arrive earlier to start the fixation, particularly for longer saccades necessarily tending to land more towards the end of the line. T3 (more numerous), T4 and T5 are the early-right-priority types. We suggest that an earlier start to a fixation constitutes a stimulus for ocular prevalence, meaning the right eye tends to assume priority in the conscious perception of the text as the reader moves from left to right across the screen. Types T6 (more numerous), T7 and T8 are the early-left-priority types; the picture is clearest in the more numerous T6. We suggest that early left-eye priority tends to reset the prevalence to the left eye at the beginning of the line.

The other aspect of asynchrony is late-priority, when one eye continues to fixate for longer: T2 (more numerous), T5 and T8 are the late-right priority types; T1 (more numerous), T4 and T7 are the late-left-priority types. We suggest that one eye continuing to fixate longer at the end of a fixation can also cue a switch in ocular prevalence or confirm an existing prevalence. In a fixation preceding a return sweep, an extended right-eye fixation may also reflect a faster abductive beginning to the saccade by the left eye.

The effects in Chinese readers are somewhat more systematic. For instance, type T1 in English readers (Table 3.4) only shows a significantly smaller distribution on the right, whereas in Chinese readers (Table 3.5) T1 shows a significantly greater distribution on the left as well as a smaller one on the right. Similarly, the T2 distribution is significantly less on the left side compared with English readers. This greater systematicity in Chinese reading might reflect the fact that Chinese text fills each line with evenly spaced characters, effectively right-justifying the text, requiring readers to proceed further across each line, into right peripersonal space.

In total, the right-priority types (English 24.5%, Chinese 23.3%) outnumber the left-priority types (English 20.0%, Chinese 18.7%) chiefly due to the more numerous T3 types compared with

T6 types. We suggest that this difference reflects the greater proportion of left-to-right (i.e. right eye abducting) saccades in the two languages.

Our data have concerned *temporal* differences in binocular coordination. How do they compare with *spatial* differences in the synchronization of the two eyes? Parker, Nikolova, Slattery, Liversedge and Kirkby (2019) review the research on spatial binocular coordination and present new data on the effects of the return sweep from the end of one line to the beginning of the next. They report larger spatial fixation disparities associated with these long return sweeps compared with shorter intra-line regressive fixations. They associate the longer line-initial fixations with lack of a parafoveal preview as opposed to the need for greater convergence. We suggest that the accumulation of T6 (left priority) fixations towards the left of our texts reflect the mechanics of eye movements, including the return sweep, as opposed to any lack of preview. We might expect some effect of the fact that the English text has a ragged right edge, reflecting differences in word length, whereas Chinese approximates to a justified right edge, reflecting the small, regular width of Chinese characters. Figures 3.3 and 3.4 show qualitatively similar distributions for T6 in the two languages, but with a denser accumulation of T6 fixations at the left of the English text. In the English texts, the distance from the end of one line to the beginning of the next was necessarily slightly shorter on average than in the Chinese, and less predictable in length and angle. These issues remain topics for further research.

We might predict that right-to-left orthographies such as Arabic and Hebrew will show a reverse effect of the predominance of early-right-priority (T3) reported here, given that the left eye in these readers will be the abducting eye in most saccades. We should see more T6 types in those readers. (See Chapter 4.)

Finally, the data suggest two questions. First, the temporal asynchronies we have measured are small, typically of the order of a few milliseconds; these measurements necessarily depend on Eyelink II technology and its algorithm for calculating saccade onset and offset. Are the differences ‘artefactual’ in some way? Understanding the process of saccade onset and offset and its empirical measurement is an ongoing research question (e.g., Bao, 2019; Hooge, Hessels, & Nyström, 2019; Hooge, Holmqvist, & Nyström, 2016; Hooge, Nyström, Cornelissen, & Holmqvist, 2015). For now, we report a predictable, interpretable pattern of temporal asynchronies arising from the mechanics of saccades as measured by Eyelink eye-tracking. The study raises further issues that are particularly relevant to reading: What types of visual processing occur at what times within fixations and saccades? Is there differential processing of high and low spatial frequencies, for instance, or of different colours? How are these different aspects of visual processing related to ocular prevalence?

Second, are the small differences we have reported relevant to processing? We suggest that the potential importance of a timing difference in the afferent sensory apparatus is not comparable to the behavioural response times in laboratory psychology tasks, where small differences can be seen as inconsequential. Rather, we are dealing with a *computational* issue in which we are trying to understand a complex system based on the firing of very large numbers of neurons mediated by even larger numbers of synapses. The evidence is that spike-timing-dependent processing can play a key role in learning (cf. Hopfield & Brody, 2004). Small differences can have big effects. We propose that these asynchronies are informative enough to drive ocular prevalence, such that the input to one or other eye may be prioritized in higher, binocularly-fused visual processing.

Further research is needed to explore the role of the physical constraints on eye movements. Overall, the analysis of ocular prevalence presented here suggests that reading relies

on *embodied* processing, such that physical constraints on eye movements are an integral part of the whole process—they are intimately connected to the ‘higher-level’ processing. The visual system is highly interconnected (cf. Van Essen, Anderson & Felleman, 1992). We also know that conscious visual experience relies on an intact V1, to which there is rich recurrent connectivity with the ‘higher’ areas.

We predict that this picture of embodied processing will become clearer as the physical set-up of reading experiments more closely approximates real-world reading. One prospective direction which we have developed involves the reading of text presented within an Augmented Reality (AR) headset, in which the viewer can experience a blend of the real-world environment and a carefully controlled virtual environment, and in which—critically—there is sophisticated monocular control of stimulus presentation. Such technology allows the independent presentation of different stimuli to the two eyes together with the integrated eye-tracking of the movements of each eye. This technology moves beyond the constraints of shutter-goggles and of physical haploscopes in presenting different stimuli to the two eyes.

Productive studies might involve the further exploration of ocular prevalence. Augmented reality technology allows the presentation of the same text to the separate eyes with a small time-delay. Our current exploration of ocular prevalence suggests that specific patterns of reading problems will be caused by delay to the left eye in the left hemifield of reading space and to the right eye in the right hemifield. Conversely, fewer problems should be caused by the switching of the delay in presentation to the non-prevalent eye. The ending of a monocular stimulus presentation can be similarly explored. Note that viewers do not typically experience awareness of the difference between monocular and binocular presentations; utricular discrimination (which eye saw the stimulus?) is also poor. Viewers simply ‘see’ the stimulus regardless.

Our emphasis in the current thesis has been on particular instances of embodied processing. AR technology allows us to explore this issue further by simulating the participant actually holding the surface (in virtual space) on which the text appears. Such a study would allow us to examine the interaction between eye movements and the movements of the arms and trunk as they affect the location of the text in virtual space. The prediction is that having multiple centres of control over the relation between text and retina will enhance processing and make its embodied nature even clearer.

Chapter 4

Reading left-to-right and right-to-left orthographies:

Ocular prevalence and orthographic conventions

Abstract

In this chapter, we analyse binocular eye-tracking data from the reading of multiline Arabic and Hebrew text. We report the distributions of small temporal asynchronies between the two eyes at the beginning and end of every fixation. We test the theory, made on the basis of left-to-right orthographies, that such asynchronies favour ocular prevalence for the left eye in the left hemifield and the right eye in the right hemifield. Ocular prevalence is the prioritizing of one eye's input in the fused binocular percept. The complex pattern of asynchronies in Arabic and Hebrew resembles that reported for the left-to-right orthographies, English and Chinese, but with particular differences that we attribute to left hemisphere specialization in word recognition or to ocular dominance. We discuss how the evident hemispheric asymmetry in parafoveal lookahead may be reflected in the nature of right-to-left orthographic conventions. We conclude that a language tends to get the orthographic conventions that the reading direction and the hemispheres deserve.

4.1 Introduction

We have compared two very different orthographies, English and Chinese, read by native speakers/readers in the previous chapter 3. The fact that the relevant fine-grain oculomotor behaviours showed a similar pattern in the two languages suggested that the behaviours were chiefly the result of the peripheral musculature responsible for horizontal eye movement, an example of 'embodied cognition' (cf. Wilson, 2002), in which the physical movement of the eyes has intrinsic implications for higher, conscious visual cognition.

However, there are important asymmetries in the visual pathways and cortical areas responsible for reading. These asymmetries involve ocular dominance (as distinct from ocular prevalence, e.g., Toosy et al., 2001; Walls, 1951) and hemispheric specialization (e.g. Coltheart, 1983; Cohen et al., 2000; Shillcock & McDonald, 2005). Are these asymmetries at all involved in the temporal asynchronies reported in chapter 2? If they are, then the reading behaviours of the RTLOs will not simply be mirror images of those of the LTROs. To answer this question, in this chapter, we compare the behaviours of the Chinese and English readers with binocular eye-tracking data from the same task in chapter 3 but involving two right-to-left orthographies (RTLOs), Arabic and Hebrew.

Cross-linguistic research on binocular coordination in reading has mainly focused on LTROs. Hsiao (2017) explored binocular disparities in English and Chinese with *temporally conjugate* fixations (i.e., RE and LE both start and end their fixations at the same time) and reports similarities and differences across the two languages. In chapter 3, we investigate *temporal disjugacy*, (i.e., the small temporal asynchronies in the two eyes' fixations) in the same eye-tracking corpus as Hsiao and discover strikingly similar distributional patterns across the two very different orthographies, for the three most numerous types of temporal asynchrony (cf. Figure 4.2, below). As reported in chapter 3, in both English and Chinese, temporally synchronized binocular fixations accounted for slightly more than half of the binocular fixations, with over 80% of binocular fixations in all ending synchronously.

How does ocular prevalence play out in reading the RTLOs Arabic and Hebrew? We tested two hypotheses:

Hypothesis (1) In RTLOs, as in LTROs, the LE will tend to begin fixating earlier and stay fixating longer in the LVF, and the RE will be similarly prioritized in the RVF, thereby facilitating the appropriate switching of ocular prevalence.

This hypothesis is based on the assumption that ocular prevalence will favour the eye that is closest and most directly square-on to the text on the screen. This analysis extends the study of the reading of the LTROs English and Chinese in chapter 3.

Hypothesis (2) The pattern of binocular temporal asynchronies in RTLOs will exactly mirror the pattern in the LTROs English and Chinese.

This strong hypothesis subsumes Hypothesis 1 and is based on the further assumption that it is the symmetrical horizontal movement of the eyes alone that is responsible for the pattern of behaviour. Any departure from exact symmetry will implicate the asymmetries in projection represented by RE ocular dominance and/or by any specialization for reading behaviours in each of the hemispheres.

The analyses were conducted on the Edinburgh 5-Language Corpus. For completeness, the details of the acquisition of the eye-tracking data are included below.

4.2 Analysis

We use the same analysis in Chapter 3 with nine typologies (cf. Figure 3.1). In this chapter, we first produced demonstrative graphs to show the distributions of the types on the screen. We then analysed the data quantitatively with GLMER models, to further characterize the specific eye-movement behaviours.

4.3 Results

We analysed a total of 138,493 binocular fixations (i.e., individual fixations by the LE and RE overlapping in time) for the Arabic readers and 82,591 binocular fixations for the Hebrew

readers, together with 160,567 binocular fixations from English readers and 158,794 binocular fixations for the Chinese readers in chapter 3. Below, we first report descriptive statistics from two perspectives: (a) the overall distribution of the different types (Figure 4.1); (b) the spatial distribution of the types across the screen on which the text stimuli were displayed. Then, we report the quantitative analysis from GLMER models from two perspectives: (a) group (i.e., language, Hebrew, and Arabic) differences; (b) screen differences under subsets of fixation types (cf. Figure 3.1) in each group of RTLOs. (c) differences between RTLOs and LTROs with different sides of the screen. Overall, the results indicate a lawful patterning of binocular behaviours relevant to ocular prevalence, across the visual field, but with some significant differences associated with reading direction.

4.3.1 Overall results

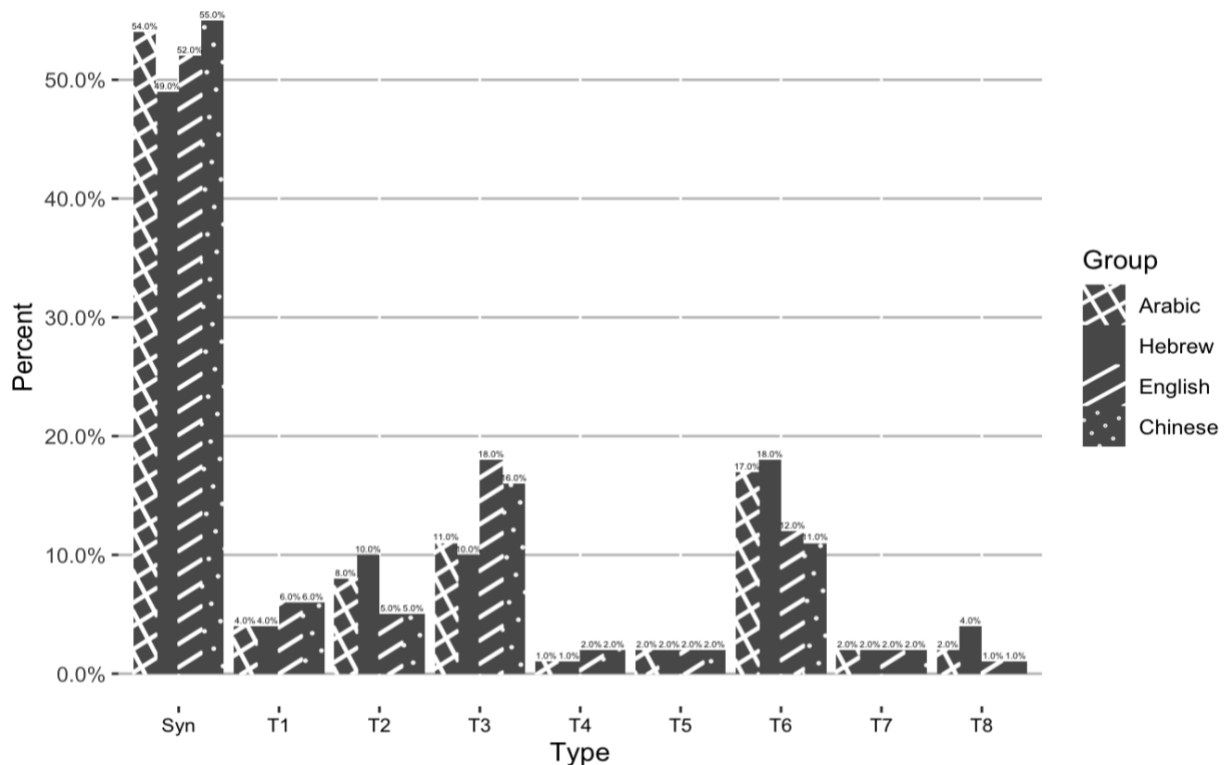


Figure 4.1 The distribution of types of asynchrony in Arabic, Hebrew, English and Chinese readers.

Syn, T3 and T6 are still the main types in all orthographies; T3 and T6 has switched distribution with left-to-right orthographies and right-to-left orthographies.

percentages for the readers of the four languages (i.e., Arabic, Hebrew, English and Chinese, the latter two taken from Zhu et al., 2021) respectively. There are visible similarities across all four languages, with the three most numerous types of binocular fixation being Syn (synchronized pairs), T3 and T6; in particular, synchronized binocular fixations account for around half the binocular fixations for all languages.

There are asymmetries depending on reading direction. English and Chinese show more T3 than T6, Hebrew and Arabic show more T6 than T3. A less pronounced interaction, with smaller numbers of fixations, may be seen for T1 and T2: English and Chinese have more T1 than T2, Arabic and Hebrew, have more T2 than T1.

4.3.2 Spatial distribution

Figures 4.2 and 4.3 show the distribution of fixation types across the lines of text, for Arabic and Hebrew, respectively. The hexbin graphs show mean coordinates (during fixation) of the right eye (RE) for each binocular fixation (the choice of RE over LE has no implications here). The distributions also show readers fixating a square at the bottom left of each page after reading it.

Similar patterns obtain for both Semitic languages. Syn, T6 and T3 show the greatest densities. There are clear differences between left, middle and right of the text.

Comparing the RTLOs (Figures 4.2 and 4.3) with the LTRO (Figure 3.3 and 3.4), the data show similarities, symmetries and departures from symmetry.

As Figure 3.1 shows, the eight non-Syn types form four symmetrical pairs in terms of the eye to which they afford priority either early or late in the fixation: T5 (RE early and late) and T7 (LE early and late); T3 (RE early) and T6 (LE early); T4 (RE early, LE late) and T8 (LE early, RE

late); T2 (RE late) and T1 (LE late). We first consider the pairs in terms of their visible distributions in Figures 4.2 and 4.3 with Figure 3.3 and 3.4.

T5 is skewed to the right and T7 is skewed to the left for both reading directions.

T3 is concentrated at the right and T6 at the left for both reading directions but T6 in English and T3 in Arabic and Hebrew are more distributed across the line.

T4 and T8 are the ‘mixed’ fixation types, which have both RE and LE priority depending on whether the start or end of fixation is concerned. T4 is skewed rightwards for Hebrew and Arabic but is more ambiguous for English. T8 is skewed leftwards for English but is more ambiguous for the Semitic languages.

T1 is skewed leftwards and T2 rightwards for both reading directions. However, T2 is distributed across the screen, but with more fixations persisting across the screen for the two Semitic orthographies. This pattern is not reciprocated with T1 in the English data.

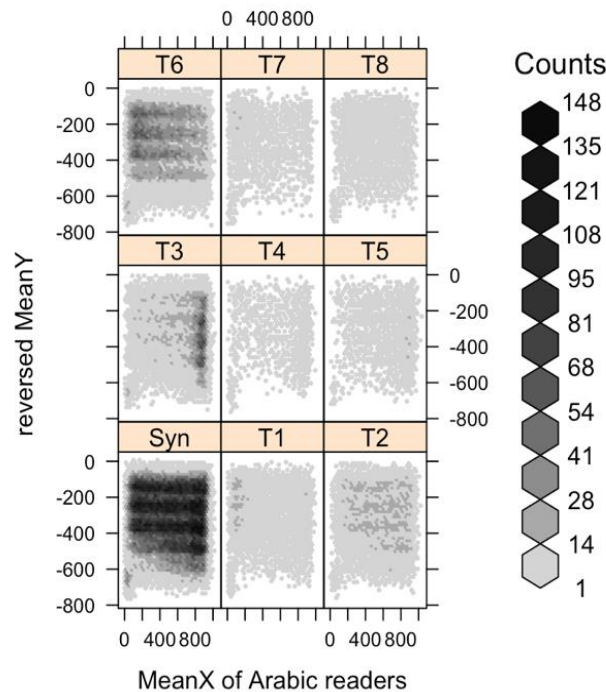


Figure 4.2 Spatial distribution of types in Arabic readers.

It shows prevalence. Left prevalent types (T1, T6, T7); Right prevalent types (T2, T3, T5).

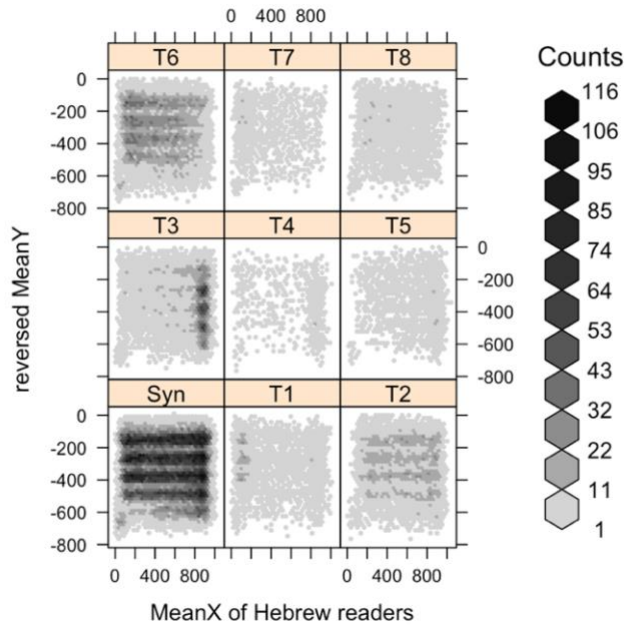


Figure 4.3 *Spatial distribution of types in Hebrew readers.*

4.3.3 Modelling results

We analysed the large volume of data in Figures 4.2 and 4.3 quantitatively. We divided the screen equally into left, middle and right regions, to investigate the distributions of fixation types across the text. We further compared the two Semitic RTLOs with the two LTROs, English and Chinese.

We use General Linear Mixed-Effects Regression Models (GLMER), carried out in R's lme4 software package (Bates, Maechler, & Dai, 2008). We used counts of fixation pairs as dependent variables in all the models. As our dependent variable was counts of events, all our modelling used Poisson error distributions. We defined null models with participants, articles and screen orders (i.e., page order of each article) as random factors. Predictor variables included fixation types (cf. Figure 3.1), the sides of the screen (left, middle and right, approximating left, middle and right of lines of text) and direction of reading (LTR for English and Chinese, RTL for Hebrew and Arabic) and tested as a whole as well as under subsets of types to explore the quantitative distribution of

the types. All Model fit was assessed using the anova function to compare models. The results show a systematic pattern of binocular behaviour across languages.

In the first part, we explored the interaction of all the types and sides of the screen altogether inclusively, in each Group (i.e., Hebrew and Arabic). In the second part, we added Group (i.e., Hebrew and Arabic, with Arabic as reference) as fixed effect to explore the group differences in our descriptive data. The models were built under subsets of Syn, T1, T2, T3 and T6 respectively. In the third part, we added sides of the screen (left, middle, right; with the middle as reference) as a predictor variable. The models were built one by one under subsets of asynchronized types to explore variation in the effects of the part of the screen on these different types, which were also tested separately within the Arabic and Hebrew data, in their own subsets. In the last part, we examined data with all four languages and added the reading direction (i.e., LTR and RTL, with LTR as reference) and sides of screen (reference varies according to the relevant distribution of types) as predictor variables. The models were built under the subset of the four most numerous asynchronized types (i.e., T6, T3, T2 and T1) and two ambiguous types (T4 and T8) separately.

The first part of inclusive modelling suggests similar ocular prevalence we found in Chapter 3, as shown in Table 4.1 and 4.2. The second part of the modelling of group differences shows both similarities and differences in the results. Group differences did not appear any qualitatively different between the two groups of readers in any other type or as a whole in the two Semitic languages, in accordance with Figure 4.2 and 4.3. The two Semitic languages elicited similar behaviours in binocular fixation-pairs in general.

In the third part of the modelling, the majority of the non-Syn types—T1, T2, T3 and T6—are similarly distributed in both groups. First, both T1 and T6 (both LE priority) have significantly more value on the left side of the screen and/or less value on the right side of the screen, compared

with the middle (i.e., the reference). Specifically, T1 in Arabic (Est= 0.1308, SE= 0.0333, $z(3514)= 3.923$, $p < .001$) and in Hebrew (Est= 0.1652, SE= 0.0440, $z(2239)= 3.753$, $p < .001$) shows a statistical concentration on the left side of the screen. Table 4.3 further shows T6 in Hebrew readers has significantly less on the right side. Similar results can be observed in Arabic readers, while additionally Arabic T6 has significantly more value on the left side.

	The number of fixations sides of screen*types
Left	-0.217 (<0.001)
Right	0.054 (<0.001)
TypeT1	-1.920 (<0.001)
TypeT2	-1.241 (<0.001)
TypeT3	-1.590 (<0.001)
TypeT4	-2.112 (<0.001)
TypeT5	-1.917 (<0.001)
TypeT6	-0.836 (<0.001)
TypeT7	-2.019 (<0.001)
TypeT8	-1.645 (<0.001)
Left:TypeT1	0.416 (<0.001)
Right:TypeT1	0.018 (0.725)
Left:TypeT2	-0.101 (0.002)
Right:TypeT2	-0.076 (0.006)
Left:TypeT3	0.068 (0.079)
Right:TypeT3	0.610 (<0.001)
Left:TypeT4	0.202 (0.080)
Right:TypeT4	0.075 (0.446)
Left:TypeT5	0.096 (0.215)
Right:TypeT5	0.114 (0.034)
Left:TypeT6	0.209 (<0.001)
Right:TypeT6	-0.523 (<0.001)
Left:TypeT7	0.527 (<0.001)
Right:TypeT7	-0.088 (0.318)
Left:TypeT8	0.178 (0.042)
Right:TypeT8	-0.294 (<0.001)
Constant	2.090 (<0.001)
Random effects	
	Variance
Participant(16)	0.0465
Article(20)	0.0014
Page(119)	0.0228

Observations	24,102
Log Likelihood	-44,458.030
Akaike Inf. Crit.	88,976.060
Bayesian Inf. Crit.	89,218.760

Note: p value in parentheses.

Table 4.1 GLMER analysis of Screen differences in Hebrew all types

	The number of fixations sides of screen*types
Left	-0.261 (<0.001)
Right	-0.028 (0.002)
TypeT1	-1.982 (<0.001)
TypeT2	-1.521 (<0.001)
TypeT3	-1.547 (<0.001)
TypeT4	-2.278 (<0.001)
TypeT5	-2.214 (<0.001)
TypeT6	-1.011 (<0.001)
TypeT7	-2.196 (<0.001)
TypeT8	-1.930 (<0.001)
Left:TypeT1	0.394 (<0.001)
Right:TypeT1	0.043 (0.246)
Left:TypeT2	0.004 (0.886)
Right:TypeT2	0.006 (0.786)
Left:TypeT3	0.057 (0.039)
Right:TypeT3	0.490 (<0.001)
Left:TypeT4	0.266 (0.002)
Right:TypeT4	0.153 (0.037)
Left:TypeT5	0.207 (0.004)
Right:TypeT5	0.201 (<0.001)
Left:TypeT6	0.332 (<0.001)
Right:TypeT6	-0.353 (<0.001)
Left:TypeT7	0.409 (<0.001)
Right:TypeT7	0.043 (0.508)
Left:TypeT8	0.178 (<0.001)
Right:TypeT8	-0.153 (<0.001)
Constant	2.253 (<0.001)
Random effects	
	Variance
Participant(28)	0.0266
Article(20)	0.0030
Page(120)	0.0235
Observations	36,383

Log Likelihood	-68,196.770
Akaike Inf. Crit.	136,453.500
Bayesian Inf. Crit.	136,708.600

Note: p value in parentheses.

Table 4.2 GLMER analysis of Screen differences in Arabic all types

GLMER analysis of Screen differences in Hebrew T6

	The number of fixations	
	null model	sides of screen
	(1)	(2)
Left		-0.011 (0.546)
Right		-0.469 (<0.001)
Constant	1.114 (<0.001)	1.236 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(16)	0.0762	0.2762
Article(119)	0.0275	0.1661
Observations	4,412	4,412
Log Likelihood	-8,559.832	-8,274.856
Akaike Inf. Crit.	17,125.660	16,559.710
Bayesian Inf. Crit.	17,144.840	16,591.670

Note: p value in parentheses.

GLMER analysis of Screen differences in Arabic T6

	The number of fixations	
	null model	sides of screen
	(1)	(2)
Left		0.077 (<0.001)
Right		-0.376 (<0.001)
Constant	1.068 (<0.001)	1.134 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(28)	0.1359	0.3687
Article(120)	0.0270	0.1645
Observations	7,034	7,034
Log Likelihood	-13,944.200	-13,541.870
Akaike Inf. Crit.	27,894.400	27,093.730
Bayesian Inf. Crit.	27,914.970	27,128.020

Table 4.3 GLMER analysis of Screen differences in Hebrew and Arabic T6

Furthermore, T2 and T3 (both RE priority) have significantly less value on the left side of the screen in both readers, and T3 also has additional significantly more value on the right side (Tables 4.4 and 4.5). The two Semitic languages again pattern very similarly.

This systematic binocular pattern is further seen in T5 (RE priority) and T7 (LE priority) in both orthographies, though the data are relatively sparse. We find significantly more value at the right side in T5 and more value at the left side in T7 in both orthographies. In particular, the results of Arabic T5 shows a significant concentration at the right side (Est=0.1442, SE= 0.0495, $z(1771)=2.908$, $p<.01$) and the same for Hebrew T5 (Est= 0.1741, SE= 0.0531, $z(1391)= 3.277$, $p<.01$), whereas the concentration for T7 is significant at the left side for both Arabic (Est= 0.1190, SE= 0.0503, $z(1794)= 2.365$, $p<.05$) and Hebrew (Est=0.2467, SE= 0.0594, $z(1207)= 4.149$, $p<.001$).

GLMER analysis of screen difference in Hebrew T2

	The number of fixations	
	null model	sides of screen
	(1)	(2)
Left		-0.340 (<0.001)
Right		-0.016 (0.515)
Constant	0.752 (<0.001)	0.840 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(16)	0.0651	0.2552
Article(119)	0.0125	0.1122
Observations	3,696	3,696
Log Likelihood	-6,090.340	-6,004.389
Akaike Inf. Crit.	12,186.680	12,018.780
Bayesian Inf. Crit.	12,205.330	12,049.850

Note: p value in parentheses.

GLMER analysis of screen difference in Arabic T2

	The number of fixations	
	null model	sides of screen
	(1)	(2)
Left		-0.285 (<0.001)
Right		-0.023 (0.302)
Constant	0.600 (<0.001)	0.679 (<0.001)
Random effects		
	Variance	Std.Dev.

Participant(28)	0.0828	0.2878
Article(120)	0.0084	0.0920
Observations	5,240	5,240
Log Likelihood	-8,155.412	-8,079.160
Akaike Inf. Crit.	16,316.820	16,168.320
Bayesian Inf. Crit.	16,336.510	16,201.140

Table 4.4 GLMER analysis of Screen differences in Hebrew and Arabic T2

GLMER analysis of screen difference in Hebrew T3

	The number of fixations	
	null model	sides of screen
	(1)	(2)
Left		-0.119 (<0.001)
Right		0.662 (<0.001)
Constant	0.850 (<0.001)	0.502 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(16)	0.0502	0.2241
Article(119)	0.0146	0.1210
Observations	3,380	3,380
Log Likelihood	-6,160.798	-5,647.221
Akaike Inf. Crit.	12,327.600	11,304.440
Bayesian Inf. Crit.	12,345.970	11,335.070

Note: p value in parentheses.

GLMER analysis of screen difference in Arabic T3

	The number of fixations	
	null model	sides of screen
	(1)	(2)
Left		-0.223 (<0.001)
Right		0.489 (<0.001)
Constant	0.930 (<0.001)	0.712 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(28)	0.0869	0.2949
Article(120)	0.0217	0.1476
Observations	5,456	5,456
Log Likelihood	-10,009.990	-9,390.262
Akaike Inf. Crit.	20,025.970	18,790.520
Bayesian Inf. Crit.	20,045.780	18,823.550

Note: p value in parentheses.

Table 4.5 GLMER analysis of Screen differences in in Hebrew and Arabic T3

In the third part of the modelling, orthographies with different reading directions show significant differences in the general distribution as well as in the four main asynchronized types – T6, T3, T2 and T1, and in the two ambiguous types – T4 and T8, with respect to different sides of the screen. The result from the general distribution (with LTRO and middle of the screen as references) shows significantly less value on the left side for the RTLOs (Est= -0.1562, SE= 0.006, $z(163344) = -23.248$, $p < .001$) and also more value on the right side (Est= 0.0787, SE= 0.006, $z(163344) = 11.801$, $p < .001$).

In the specific types, Table 4.4 (with LTRO and right of the screen as references) shows significantly less on the left side but significant more in the middle of the screen in the RTLOs in T6 (early-LE-priority) for the RTLOs, which is in accordance with the expanded distribution of T6 across the line in Figures 4.2 and 4.3, compared with Figure 3.3 and 3.3. On the other hand, T3 (early-RE-priority) as shown in Table 4.5 (with LTRO and left of the screen as references) suggests the opposite significant change, with statistically less in the middle but more on the right side of the screen, for the RTLOs. In addition, the distribution of T2 (late-RE-priority) across the line also shows significance in Table 6 (with LTRO and left of the screen as references) at both middle and the right side of the screen in the RTLOs, whereas T1 (late-LE-priority) shows significantly more value at both left and right sides of the screen in RTLOs (with LTRO and middle of the screen as references) in Table 4.7. This modelling bears out the visual interpretation of Figures 4.1 and 4.2.

	The number of fixations reading directionsides of screen*reading direction	
	(1)	(2)
Right to Left	0.275 (<0.001)	0.375 (<0.001)
Left		0.695 (<0.001)
Middle		0.161 (<0.001)
RTL:Left		-0.242 (<0.001)
RTL:Middle		0.248 (<0.001)
Constant	0.820 (<0.001)	0.397 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(128)	0.0848	0.2912
Article(82)	0.0220	0.1483
Screen(5-9)	0.0010	0.0331
Observations	27,550	27,550
Log Likelihood	-51,161.450	-48,750.650
Akaike Inf. Crit.	102,334.900	97,521.300
Bayesian Inf. Crit.	102,384.200	97,603.540

Note: Screens differ for the article and as random slope.

Table 4.6 GLMER analysis of differences in direction of reading T6

	The number of fixations reading direction sides of screen*reading direction	
	(1)	(2)
Right to Left	-0.055 (0.309)	-0.288 (<0.001)
Middle		0.255 (<0.001)
Right		0.328 (<0.001)
RTL:Middle		-0.070 (<0.001)
RTL:Right		0.406 (<0.001)
Constant	0.957 (<0.001)	0.744 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(128)	0.0748	0.2735
Article(82)	0.0221	0.1486
Screen(5-9)	0.0019	0.0441
Observations	29,349	29,349
Log Likelihood	-53,546.840	-51,934.880
Akaike Inf. Crit.	107,105.700	103,889.800
Bayesian Inf. Crit.	107,155.400	103,972.600

Note: Screens as random slope.

Table 4.7 GLMER analysis of differences in direction of reading T3

	The number of fixations reading directionsides of screen*reading direction	
	(1)	(2)
Right to Left	0.303 (<0.001)	0.182 (<0.001)
Middle		0.021 (0.328)
Right		0.198 (<0.001)
RTL:Middle		0.287 (<0.001)
RTL:Right		0.090 (<0.001)
Constant	0.367 (<0.001)	0.263 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(128)	0.0469	0.2166
Article(82)	0.0022	0.0474
Observations	19,899	19,899
Log Likelihood	-28,822.090	-28,591.260
Akaike Inf. Crit.	57,652.190	57,198.530
Bayesian Inf. Crit.	57,683.780	57,261.720

Note: p value in parentheses.

Table 4.8 GLMER analysis of differences in direction of reading T2

In addition, the two ambiguous types T4 (early-RE-priority and late-LE-priority) and T8 (early-LE-priority and late-RE-priority) also show differences between languages according to reading direction. Specifically, the RTLOs show significantly more fixations on the right of the screen in T4 (Est= 0.1919, SE= 0.0656, $z(6960)= 2.925$, $p < .01$). On the other hand, T8 shows a relatively greater concentration in the middle for the RTLOs, with both less on the left (Est= -0.1406, SE= 0.0527, $z(7680)= -2.665$, $p < .01$) and less on the right (Est= -0.2066, SE= 0.0584, $z(7680)= -3.528$, $p < .001$). As Figure 4 shows, this pattern is the converse of that found for the LTROs.

	The number of fixations reading directionsides of screen*reading direction	
	(1)	(2)
Right to Left	-0.061 (0.103)	-0.157 (<0.001)
Left		0.065 (<0.001)
Right		-0.246 (<0.001)
RTL:Left		0.081 (<0.001)
RTL:Right		0.280 (<0.001)
Constant	0.441 (<0.001)	0.460 (<0.001)
Random effects		

	Variance	Std.Dev.
Participant(128)	0.0323	0.1799
Article(82)	0.0016	0.0411
Observations	18,392	18,392
Log Likelihood	-25,060.780	-24,909.780
Akaike Inf. Crit.	50,131.570	49,835.570
Bayesian Inf. Crit.	50,170.670	49,898.120

Note: p value in parentheses.

Table 4.9 *GLMER analysis of differences in direction of reading T1*

4.4 Discussion

We have analysed the distribution of small temporal asynchronies of binocular fixation in the reading of continuous multiline text in two right-to-left orthographies (RTLOs), Arabic and Hebrew, and we have compared them with the same type of data from two left-to-right orthographies (LTROs), English and Chinese. We tested the hypothesis that the right eye (RE) would tend to begin fixating first and/or end fixating second on the right side of the text, and conversely that the left eye (LE) would tend to begin fixating first and/or end fixating second on the left side of the text. This hypothesis was based on the theory (Anon et al., 2021) that: (a) ocular prevalence is just as present in reading as in typical scene viewing; (b) reading benefits from ocular prevalence, such that the eye that is closest and squarest-on to the text has priority in the conscious fused percept of the text; (c) small binocular timing asynchronies contribute to ocular prevalence moving fluidly between the two eyes in skilled reading. There are three aspects to our results.

(1) *Ocular prevalence.* Arabic and Hebrew reading behaviours matched our predictions concerning ocular prevalence. Overall, the pattern of temporal asynchronies in the RTLOs closely resembled those of the previously reported LTROs: the RE's input tends to be prioritized on the right side of the screen and the LE's on the left side (Figures 4.2 and 4.3).

(2) *Reading direction and symmetry.* There is an overall quantitative *symmetry* of the data for the two directions of reading. Fixation types T3 and T6 in Figure 4.2 best demonstrate this left-right reversal of the pattern of asynchronies, but we also see this symmetry in the less numerous pairs of types. This symmetry is a critical confirmation of our claim that the observed asynchronies in LTROs resulted from anatomical constraints interacting with the direction of reading.

Our theory of the role of ocular prevalence in reading is based on the speed and power of the lateral rectus muscle. It guarantees that *abductive* movement (away from the nose) of either eye has greater acceleration than *adductive* movement (towards the nose), in the horizontal plane (Robinson, 1964). In a LTRO, this acceleration means that the abducting RE is likely to saccade away from a fixation more promptly, leaving the LE still fixating (a late LE priority). The RE is also likely to arrive at the next fixation more promptly, allowing it to begin fixating earlier (an early RE priority). This situation is reversed for the return sweep and for regressive saccades within a line of a LTRO, when the LE becomes the abducting eye. The effects of the speed and strength of the lateral rectus muscle will tend to be more evident in longer saccades, which necessarily fall more towards the right or left extremes of a line (depending on reading direction) because such a landing position affords more scope for longer saccades. Figures 4.2 and 4.3 show just such concentrations of the non-Syn types. In RTLOs there are progressively more T6 fixations (making the LE the prevalent eye) as the reader progresses leftwards and in LTROs progressively more T3 fixations (making the RE the prevalent eye) in the rightward direction of reading. The complementary T3 fixations in RTLOs and T6 fixations in LTROs show a dense patterning largely accounted for by the respective return sweeps.

T4 (early RE & late LE priority) and T8 (early LE & late RE priority) are ‘mixed’ types. They potentially reveal the relative importance of early and late priority in determining prevalence. T4 are skewed to the right of the screen for the RTLOs. The complementary T8 predominate on the left for LTROs. This pattern is in line with an *earlier start* to fixation—as opposed to a late end—predicting prevalence; overall, binocular fixations that *begin* asynchronously make up some one-third of the total.

When we look at the converse interaction of these two types with reading direction, we again see symmetry: T8 in the RTLOs and T4 in the LTROs tend to cluster in the middle of the screen, suggesting their mixed nature with regard to switching prevalence may assert itself more in the middle of the screen where pressure to switch prevalence is subtlest.

Binocular fixations with precisely synchronized starts and ends constitute the modal behaviour for both directions of reading. Syn sustains the current ocular prevalence. Typically, the status quo is optimal.

(3) *Departures from symmetry.* There are quantitative departures from this very salient symmetry. They are associated with direction of reading and are most clearly seen in comparing the distributions of the complementary types T1 and T2.

T1 and T2 have fixation ends that favour the LE and RE respectively. The modelling showed two unexpected departures from symmetry in RTLOs: there were more T1 at both left *and right* sides of the screen and there were more T2 in the *middle* of the screen than would be expected.

There are two very relevant anatomical and behavioural asymmetries in the reading system. First, *ocular dominance* (chiefly of the RE, over the population) refers to the long-term preference of one eye in sighting tasks (Porac & Coren, 1976). Second, *hemispheric specialization* of the LH for phonological and lexical processing. In addition, the overwhelming majority of fixations in our

data were ‘crossed’ in which the LE fixates to the right of the RE. These facts suggest interpretations of the observed asymmetries.

A relative concentration of T1 on the right of the screen means a LE prevalence at the beginning of the line in a RTLO; fixations begin synchronously and the LE stays fixating longer. (In the LTROs T2 fixations do not exhibit the converse behaviour to T1 in RTLOs.) We suggest that this T1 sub-population is adaptive because it means the RE moving leftwards onto new text sooner. In addition, the RE has an adaptive direct contralateral projection of its right visual field (RVF) to the lexically privileged LH. Such an early movement by the RE is *adductive*, meaning it is not facilitated by the powerful lateral rectus muscle, but we suggest it is facilitated by the RE typically being the dominant eye.

In RTLOS, T2 in the middle of the screen means a RE prevalence persisting from the right side of the screen: fixations begin synchronously and the RE stays fixating longer. We interpret this pattern as the RE taking advantage of having first access to the previously unseen text on the left and of having a direct contralateral projection to the LH. Again, we attribute the RE’s ability to do this to its being typically the dominant eye.

Embodied cognition. It is physically impossible for the muscular control of the eyes to guarantee 100% precise coordination of fixation onsets and offsets. The 50% level of Syn responses is itself impressive. However, the departures from complete control contribute *adaptively* to the high-level division of labour between the eyes, represented by ocular prevalence. The concept of ‘embodied cognition’ has been used in a variety of ways (Wilson, 2002). The relationship we have described between the physical movement of the eyeballs and the conscious perception of the text is one such example. Conscious perception depends on ocular prevalence and the latter is an integral part of how the two eyes are necessarily co-ordinated.

Orthography and the hemispheres. We return to the issue of the asymmetry between lexical processing in the two hemispheres and the direction of reading. In a crossed fixation in a LTRO, the farthest lookahead into the upcoming text is from the LE and is directly projected contralaterally into the lexically privileged LH, albeit from an ipsilateral projection from the LE. But in a RTLO, the farthest lookahead is from the RE, directly projecting to the RH; only the ‘backwards looking’ RVF of the RE projects to the LH. Note that even in a rarer uncrossed fixation, the projection of the then-leading LE’s LVF is still to the RH. Is this early reliance on the RH a problem for readers of a RTLO?

If reading simply involved accessing the lexical representations of the LH, then RTLOs would seem maladaptive in terms of the farthest lookahead. However, a number of hemispheric differences are potentially relevant to reading. Some may favour early LH involvement, like categorical lexical processing. There is also a LH preference for the horizontal (Pettigrew, 2001), a capacity for focal attention (e.g. Weissman & Woldorff, 2005), a pre-eminent network of phonological, semantic and syntactic processing (Vigneau et al., 2006), a propensity for categorical perception (Holmes & Wolff, 2012), inferencing based on coherence (Beeman, Bowden & Gernsbacher, 2000), speed of executing routinized processing (Goldberg & Costa, 1981), processing of categorial spatial relations (Kosslyn, 1987), frequency-based elimination of lexical ambiguity (Burgess & Simpson, 1988), and the capacity for ‘fine-coding’ (Beeman et al., 1994). All these appear to favour the privileged access to the LH in LTR reading.

In contrast, there are hemispheric differences that might favour RTLOs and direct projection to the RH. They include the ability to span the visual field more widely than the LH, attending to both extremes of the perceptual window (an example of the more general ability of the RH to incorporate aspects of LH processing) (Ellis, Jordan & Sullivan, 2006; Somers &

Sheremata, 2013), the capacity for ‘coarse-coding’ (Beeman et al., 1994), predictive inferencing (Beeman, Bowden & Gernsbacher, 2000), processing of coordinate spatial relations (Kosslyn, 1987), the capacity to deal with blurred images (Cowin & Hellige, 1994), processing of fleeting letter images (Hellige & Webster, 1979), multiple activation in cases of lexical ambiguity (Burgess & Simpson, 1988), and the processing of novelty (Goldberg & Costa, 1981). (Although note that many of the experiments demonstrating hemispheric differences will have been performed on participants with a history of solely reading LTROs; it is conceivable that extended exposure to RTLOs may affect some differences in some tasks.)

An important suggestion by Peleg, Manevitz, Hazan and Eviatar (2010) concerns the claim that in the RH there is a *disconnection* between orthographic and phonological processing, as opposed to an *absence* of phonological processing (although see, e.g., Vigneau et al., 2011). Such a hemispheric asymmetry facilitates processing of non-dominant meanings of homographs in the RH, particularly when there is disambiguating context, because there is no frequency-trained phonological processing to create powerful attractors within orthographic-phonological processing to select the dominant meaning. Such a hemispheric asymmetry is advantageous for the processing of words with no explicit vowel information and therefore with a high proportion of homographs in the lexicon, both homophonic (e.g., ‘bank’) and heterophonic (e.g. ‘bow’).

Thus, there are pros and cons regarding reading direction. Historically, the orthographies of the world have been written and read in a variety of directions— boustrophedon (‘ox-turning’) alternated RTL and LTR with each line. Direction has been determined partly by the material technology of making marks and by the physicality of handedness. The phonological form of words in a language may favour a direction of writing; further, with a direction of reading in place, we can expect the exigencies of foveal splitting and hemispheric differences to assert themselves

over cultural time, to ‘give the hemispheres the orthography they deserve’. Specifically, we might expect the farthest lookahead going directly to the RH to elicit orthographic conventions that match the known processing propensities of the RH.

Coarse-coding means that any one processing unit responds to a wider range of inputs than does a fine-coding processing unit. There is longstanding evidence that the RH is more predisposed to coarse-coding than is the LH. We can expect that this capacity will interact with the cultural evolution of reading, in particular with the direction of reading. Contralateral projection of the line of text to the two hemispheres means that there will be occasions when the RH receives text that the LH has not yet seen or has not yet fully processed. If the processing required involves the use of context of any sort (visual, phonological, semantic) then we can expect the RH to do that processing well and this confirm the direction of reading that led to that input. Below, we list several examples of such contextual processing that occur specifically in RTLOs and which we can expect the RH to be particularly good at processing.

A RTLO may exploit the RH’s capacity for coarse coding, for taking *context* of all kinds into account (cf. Beeman et al., 1994). We see this feature in Arabic and Hebrew. First, both have ‘unpointed’ forms for skilled readers; the whole word is compressed into a shorter span, the vowels being inferred from the word’s triconsonantal root and from lexical and sentential context. Unpointed versions of Arabic and Hebrew texts are typically shorter than English by some one-third. Thus, for the same physical fixation disparity in reading English, a LTRO, the reader can access more information in the same size of parafoveal lookahead. Second, Arabic words tend to be semantically dense, containing complex meanings (AlJassmi, Hermena & Paterson, 2021). Third, Arabic weaves its morphology non-concatenatively between the consonants of the root. Fourth, Arabic consonants have position-specific forms, such that position in the word informs the

identity of the letter. Fifth, (although only in ornate calligraphy) Arabic letters may be vertically superimposed on each other. Sixth, a cursive form predominates in Arabic. These six instances of the role of context all concern the RH's association with coarse coding. Finally, cortical processing is plastic in the face of repeated stimulation of a particular type. Ibrahim and Eviatar (2009) show a sensitivity to morphological complexity in *both* hemispheres in Arabic and Hebrew lexical processing, in contrast to English readers. This sensitivity may reflect the fact that complex morphology is constantly being projected parafoveally to the RH in reading Arabic and Hebrew (cf. Deutsch, Frost, Pelleg, Pollatsek & Rayner, 2003; Rima, Kerbyson, Jones & Schmid, 2020), or it may be that any such propensity in LTR readers is simply lost because it is needed much less.

The converse arguments apply with respect to LTROs and the strengths of the LH. Word recognition takes advantage of the full orthographic specification of words. The phonology of vowels is processed parafoveally (Schotter, Angele, & Rayner, 2012). As stated above, there is the caveat that the comparison of reading behaviours with respect to reading direction is currently far from comprehensive.

In conclusion, we compared multiline binocular reading analyses from previous chapter for left-to-right orthographies (LTROs) English and Chinese with comparable data from right-to-left orthographies (RTLOs) Arabic and Hebrew. We found that the theory of ocular prevalence discussed in Chapter 3 holds for both directions of reading. The furthest text lookahead in reading RTLOs is projected directly to the right hemisphere (RH). We suggest that various aspects of RTLOs match the RH's processing propensities and may owe their cultural evolution to this fact: a language tends to get the orthographic conventions that the reading direction and the hemispheres deserve.

Further experiments can be conducted on Arabic and Hebrew, similar to those suggested at the end of Chapter 3. In addition, higher cognition, at the level of different orthographies, does produce somewhat different patterns of data beyond the general role of ocular prevalence. We have suggested that detailed lexical processing that involves the use of context (e.g. omission of vowels in ‘unpointed’ text, or different forms of the same letter at different positions in the word) should benefit from projection to the right hemisphere. One experiment that might usefully explore this claim would involve comparing the reading of typical Hebrew texts with Hebrew texts constructed so as to maximise the use of such contexts. Pointed versus unpointed text would be an example of such a contrast. The prediction is that the distribution of types of binocular fixation, as in our typology, should be affected by these changes in text in which the right hemisphere’s contextual processing is less relevant.

Chapter 5

Binocular disparity behaviours in response to contrast changes in a reading-like task

Abstract

In this chapter, we investigate how the visual system reacts and adapts to a continuous text-background contrast in a number reading task. In the reading-like task, the background becomes more and more faded while the text stimuli stay bright and white, with decreasing contrast and increasing reading difficulty. We found a systematic adaptation of binocular vision in response to the contrast change, with an overall crossed tendency of binocular fixations, both qualitatively and quantitatively. We suggest these overall behaviours suggest a potential processing advantage for crossed fixations. The binocular contrast adaptation through very peripheral muscle-driven movements of the eyes implies an effect in which the cortical processing that contributes to cognition is also synchronised with the neural circuits controlling eye-movements. These data indicate a systematic and harmonious visual activity showing the flexibility of the visual system across different modes of operation.

5.1 Introduction

In Chapter 1, we have discussed the influence of text-background contrast on visual performance. The change in binocular performance in processing stimuli is reported to be elicited by the variation of text-background contrast in both reading (Legge et al., 1990; Johansson et al.,

2014) and non-reading (Blythe et al., 2009; Kirkby et al., 2010; Liversedge, Rayner, et al., 2006) tasks.

How would contrast influence eye movements in reading specifically? Ding et al. (2013) has suggested a disparity-related influence in perceiving contrast in their computational visual models. Little has been explored to understand the influence of contrast variation on the specific binocular behaviour of fixation disparity. In addition, it has been reported that the specific levels of contrast influence the reading performance (Fujita et al., 2008). Therefore, a continuous change condition of text-background contrast might facilitate our understanding of this effect.

Therefore, we investigated how binocular disparity related behaviour would respond to variation of contrast during reading. We tested two hypotheses:

Hypothesis (1) A majority of fixations overall will be crossed (right eye's fixation to the left of the left eye's fixation).

This hypothesis is predicated on Shillcock et al.'s (2010) theory that crossed fixations are the norm for general levels of illumination close to normal room lighting, that such fixations benefit the reader by overlaying the two privileged contralateral projections in the middle of the perceptual window for reading, and that the majority uncrossed fixations reported for dual-purkinje binocular eye-tracking reflect the fact that complete darkness is required in such experiments, creating a greater challenge for binocular fusion, which is resolved by uncrossed fixations which bring the plane of the image between the reader and the horopter.

Hypothesis (2) Binocular disparity adapts to variation in text-background contrast. We expect more crossed fixations and smaller disparities as the contrast gets lower and reading difficulty increases.

This hypothesis is predicated on the fact that the quality of the visual information reaching the brain is improved by (a) exploiting the central part of the perceptual window (as in Hypothesis 1), and by binocular fusion. Binocular fusion for ambiguous input such as the lower contrast parts of the stimulus will be improved by a smaller fixation disparity, meaning that there is greater overlap between the foveal input from the two eyes.

5.2 Analysis

Figure 5.1 demonstrates the positions along the digit line where participants are unable to continue reading. We first produced demonstrative graphs to show the distributions of the binocular eye movement behaviours. We then analysed the data quantitatively with GLMER and LMER models, to further characterize the eye-movement behaviours under the specific conditions.

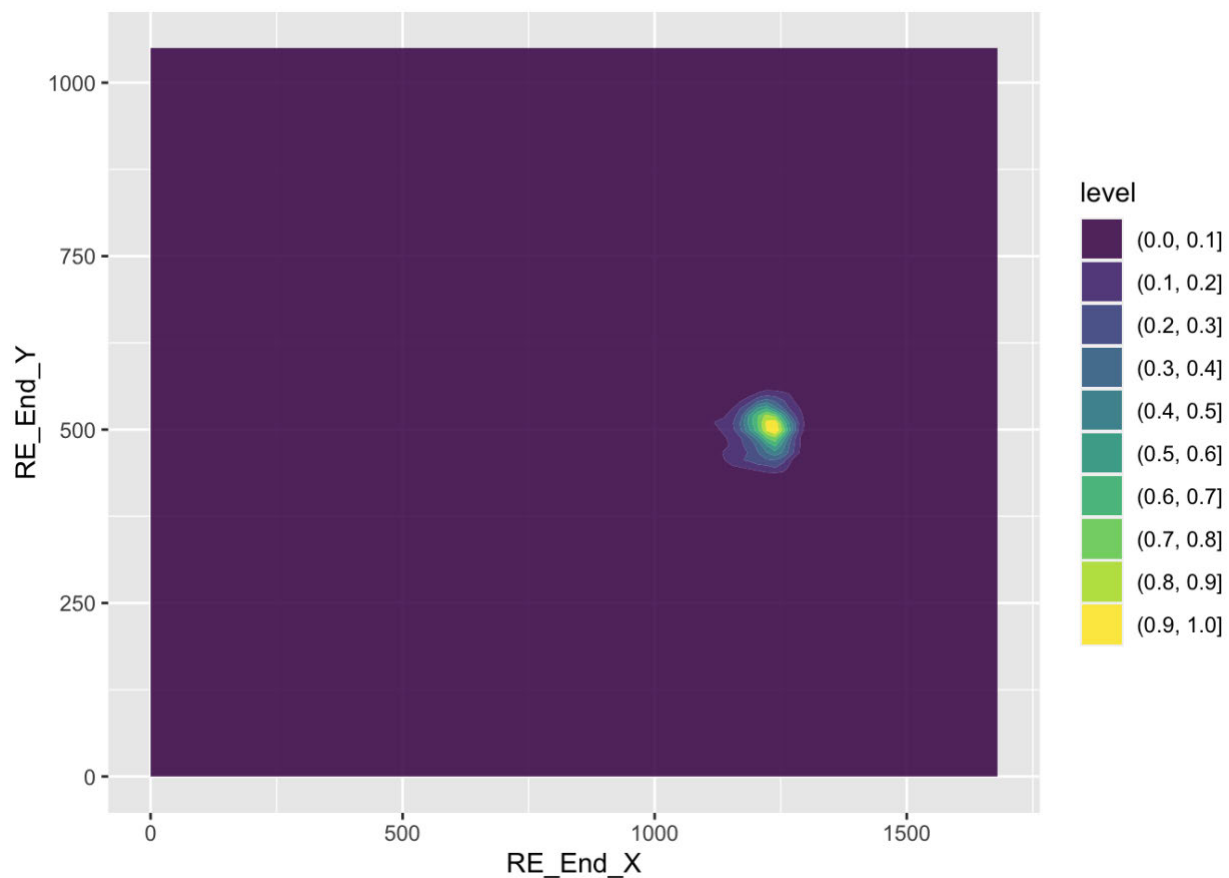


Figure 5.1 The heatmap of locations where the participants find difficult to continue reading.

5.3 Results

We analysed a total of 54,456 binocular fixations. We report the results from four perspectives together with descriptive statistics and modelling statistics: (a) vergence within the fixation (i.e. convergence vs. divergence); (b) fixation disparity at the beginning and the end of fixations (i.e. C-C, U-U, C-U, U-C); (c) change of disparity during the fixation; (d) mean pupil size of the fixation in the left eye and right eye.

In the modelling results, both Linear Mixed-Effects Regression Models (LMER) and General Linear Mixed-Effects Regression Models (GLMER) were used for quantitative analyses, carried out in R using the lme4 software package (Bates, Maechler, & Dai, 2008). In the GLMER modelling, we used counts of binocular fixations as dependent variables in the models. We defined null models with participants and trials as random factors. Predictor variables included the type of vergence movement during the fixation (convergence—the lines of sight from the eyes moving towards the nose; divergence—the lines of sight from the eyes moving away from the nose), the type of disparity including C-C (i.e. crossed at both the beginning and end of fixation) and U-U (i.e. uncrossed at both the beginning and end of fixation) and the horizontal extent of the screen divided into three equal parts (A1, A2, A3 with reading difficulty: $A1 < A2 < A3$). In the LMER modelling, we used the change of disparity (i.e., the fixation disparity at the end of fixation minus the disparity at the beginning) as the dependent variable in the models. We defined null models with participants and trials as random factors. Predictor variable includes the horizontal extent (A1, A2, A3) of the trial. All Model fit was assessed using the anova function to compare models.

5.3.1 Vergence movement in different viewing areas

Figure 5.2 shows the distribution of disparity in different areas (i.e., A1, A2, A3). The reading difficulty increases as participants read from A1 to A3. A3, as most difficult area to read, shows the lowest proportion of convergence. There is also an increased distribution of convergence as the reader views from A1 to A2. Both areas are still able to be read naturally regardless of increased difficulty. A2 shows the highest converging distribution among the three areas. This higher amount of convergence is statistically significant, as shown in Table 5.1 (A2 and divergence as references). The distribution of converging fixations in A1 and A3 are significantly less than that in A2.

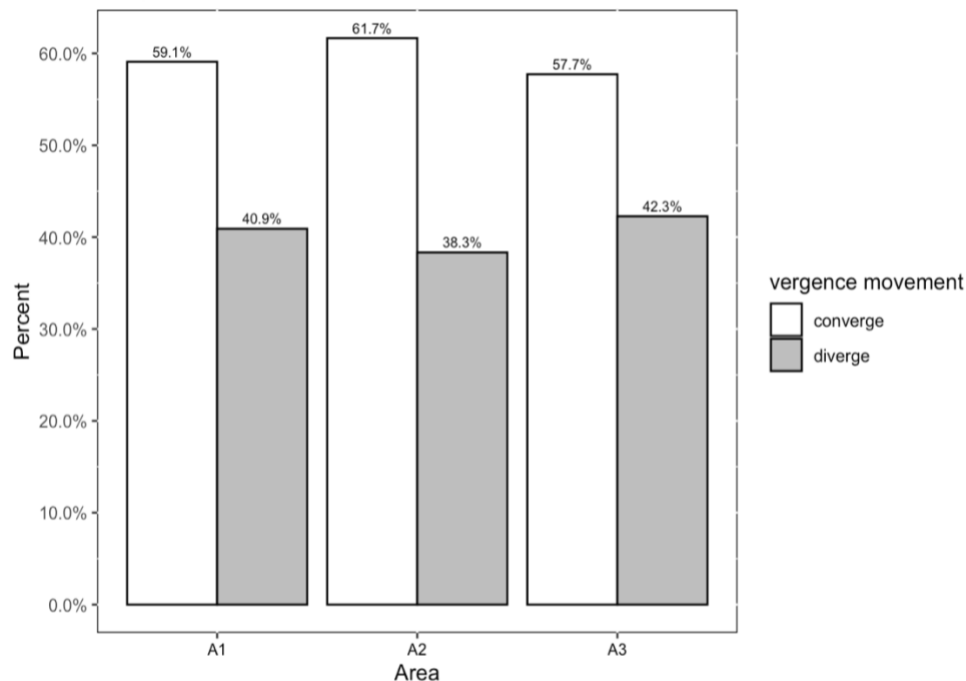


Figure 5.2 The distribution of vergence under each viewing area. A2 shows highest convergence distribution among all.

	The number of fixations	
	null model (1)	vergence*area (2)
A1		0.139 (<0.001)
A3		0.110 (<0.001)

converge	0.384 (<0.001)	0.475 (<0.001)
A1:converge		-0.108 (<0.001)
A3:converge		-0.164 (<0.001)
Constant	5.041 (<0.001)	4.956 (<0.001)
<hr/> Random effects		
	Variance	Std.Dev.
Participant(38)	0.0325	0.1804
Observations	228	228
Log Likelihood	-2,699.317	-2,652.364
Akaike Inf. Crit.	5,404.634	5,318.728
Bayesian Inf. Crit.	5,414.922	5,342.733
<hr/>		
<i>Note: p value in parentheses.</i>		

Table 5.1 *GLMER analysis of distribution of vergence in each viewing area*

5.3.2 Disparity type at the beginning and end of fixation

Figure 5.3 shows the distribution of the type of disparity at the beginning and end of fixations, with crossed (C) and uncrossed fixations (U). Two types including both the beginning and the end as crossed fixations (C-C) and both as uncrossed fixations (U-U) are the dominant fixation types. While the C-C fixation type shows an increase from A1 to A3, the U-U fixation type decreased gradually. The comparison of A1 and A3 as the easiest and the hardest area to read shows the greatest difference. Statistical models with two main areas (A1, A3) and types (C-C, U-U) from Table 5.2 further supported the difference of this distribution in the type of binocular fixation pairs at the beginning and end of fixation under each area (A1 and U-U as references). Similar to the descriptive analysis, the model shows significantly more C-C values in the area of A3, compared with reading in A1.

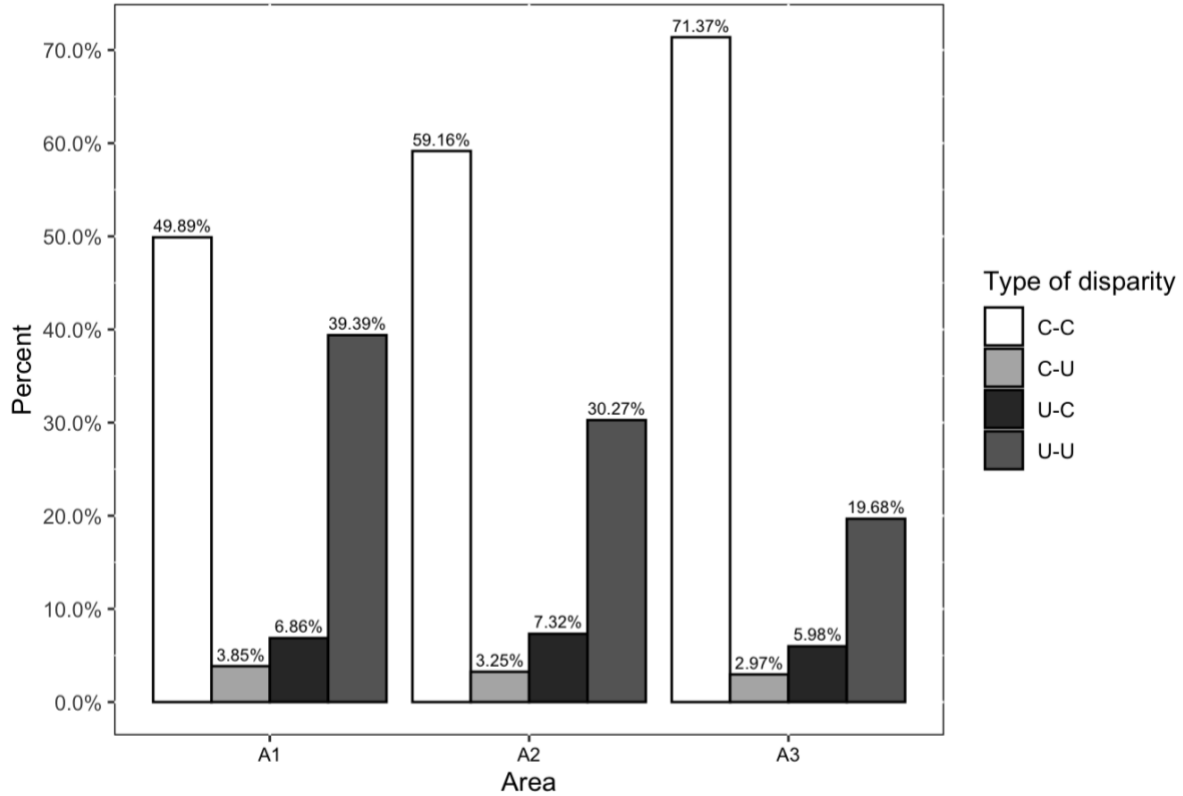


Figure 5.3 The distribution of disparity type at the beginning and end of fixations. Crossed-Crossed disparities show predominance in all areas.

	The number of fixations	
	(1)	(2)
	No interaction	disparity*area
A3	0.003 (0.824)	-0.633 (<0.001)
C-C	0.583 (<0.001)	0.179 (<0.001)
A3:C-C		0.930 (<0.001)
Constant	4.852 (<0.001)	5.100 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	0.0580	0.241
Observations	145	145
Log Likelihood	-7,948.150	-7,345.485
Akaike Inf. Crit.	15,904.300	14,700.970
Bayesian Inf. Crit.	15,916.210	14,715.850

Note: p value in parentheses.

Table 5.2 GLMER analysis of distribution of disparity types in the viewing area

5.3.3 Disparity at the beginning and end of fixation

Figures 5.4 and 5.5 show the specific disparity distribution at the beginning and the end of fixations in each area respectively. The negative value indicates crossed fixation pairs (i.e., right eye at the left side of the left eye). The graphs show gradual movement to the negative value from A1 to A3, suggesting overall crossed fixations as the eyes view from left to right, in both beginning and end of fixations, though the end of fixation shows an even deeper trend of negativity. Tables 5.3 and 5.4 further report this trend statistically, in which the disparity of A1 and A3 is significantly more and significantly less than that in A2, respectively. These results all suggest a gradual decrease of the disparity when reading from left to the right and overall more crossed fixations, in accordance with the findings above.

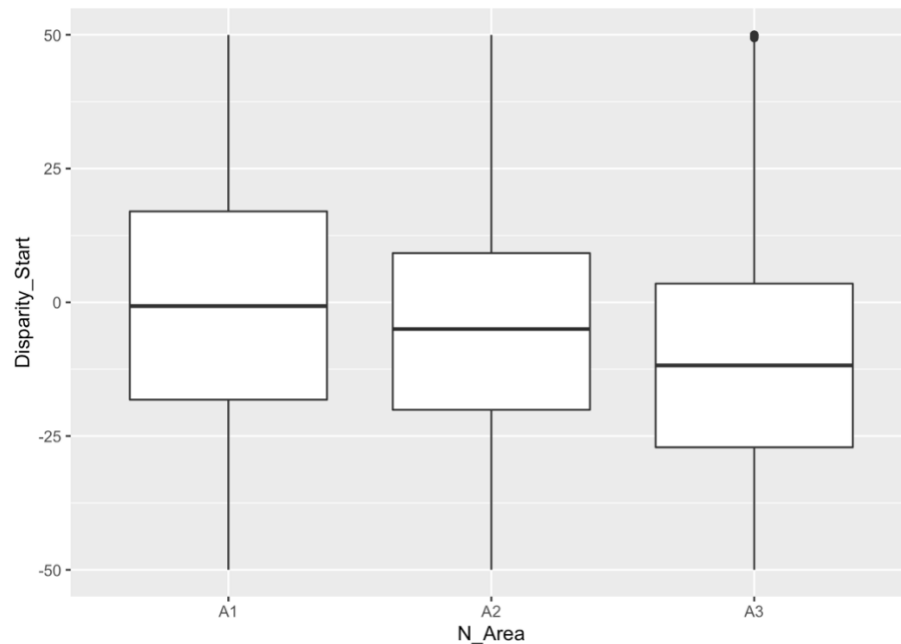


Figure 5.4 *The disparity at the beginning of fixations under each area. The value becomes more negative from A1 to A3.*

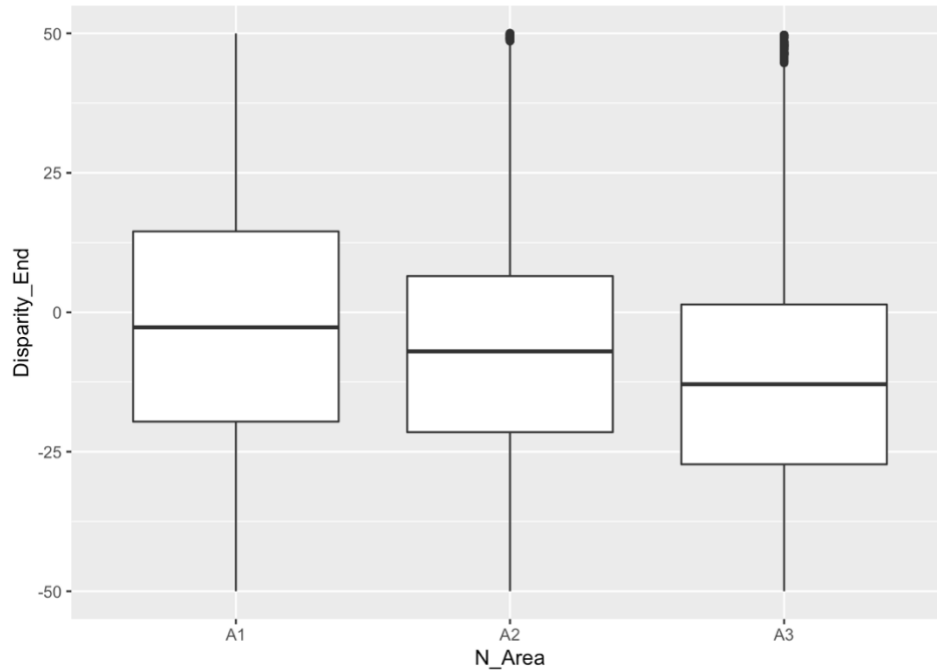


Figure 5.5 The disparity at the end of fixations under each area.
Similar trend can be found at the beginning and the end.

The disparity		
	null model	areas
	(1)	(2)
A1		7.514 (<0.001)
A3		-11.437 (<0.001)
Constant	-12.740 (0.003)	-11.798 (0.006)
Random effects		
	Variance	Std.Dev.
Participant(38)	676.7	26.01
Trial(20)	5.355	2.314
Observations	44,197	44,197
Log Likelihood	-209,022.300	-207,212.400
Akaike Inf. Crit.	418,052.500	414,436.800
Bayesian Inf. Crit.	418,087.300	414,489.000

Note: p value in parenthesis.

Table 5.3 LMER analysis of disparity at fixation start

The disparity		
	null model	areas
	(1)	(2)
A1		7.726 (<0.001)
A3		-11.063 (<0.001)

Constant	-15.123 (0.004)	-14.375 (0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	660.2	25.69
Trial(20)	5.314	2.305
Observations	44,197	44,197
Log Likelihood	-208,314.100	-206,480.600
Akaike Inf. Crit.	416,636.200	412,973.300
Bayesian Inf. Crit.	416,671.000	413,025.400
<i>Note:</i> p value in parentheses.		

Table 5.4 *LMER analysis of disparity at fixation end*

5.3.4 Mean pupil size

The mean pupil size of the left and the right eye showed a very similar feature, with gradually decreasing pupil size reading from left to right. Overall smaller pupil size can be seen in A3, compared with A1 and A2. The statistical modelling results indicates significantly smaller right eye pupil size of A3 (Est= -129.424, SE= 1.844, $t(44197) = -70.18$, $p < .001$) and greater value of A1 (Est= 86.693, SE= 1.786, $t(44197) = 48.53$, $p < .001$) in comparison with A2. A similar result can be seen in the left eye with greater mean pupil size in A1 (Est= 166.86, SE= 2.024, $t(44197) = 82.42$, $p < .001$) and smaller size in A3 (Est= -186.527, SE= 2.09, $t(44197) = -87.34$, $p < .001$). These results all suggest an overall gradual decrease of pupil size as reading proceeds from A1 to A3.

5.4 Discussion

We have found an overall crossed tendency of binocular fixations as the text-background contrast decreases gradually and reading difficulty increases, both qualitatively and quantitatively. The rate of change of this binocular movement becomes highest in its mean contrast area (A2), suggesting a binocular adaptation in response to contrast variation during the reading process. The highest contrast area (A1) shows the greatest proportion of uncrossed fixations. The movement

from A1 to A2 indicates an increasing disparity of the crossed fixation as they become more crossed. The lowest contrast area (A3) generates the highest number of crossed fixations and also more negative crossed distance disparity compared with the previous area (A2). These overall behaviours suggest binocular contrast adaptation and a potential processing advantage for crossed fixations.

In region A1 on the left of the screen, the fixation disparity has the largest proportion of uncrossed, compared with the later areas with lower contrast. This is as we would predict because the background is dark, which is also consistent with previous findings when the background is dark in the research on binocular reading (Liversedge, White, et al., 2006; Kirkby et al., 2013). In these reading experiments there was relatively little information, in terms of visual context, to support the accurate fusion of the visual input to the two eyes. Accordingly, the left and the right eye are in an uncrossed fixation because this places the virtual point at which the lines of sight from the two eyes converge beyond the surface of the screen. That is, the text to be read is placed inside the horopter. This is the zone that supports the most robust fusion. The capacity to fuse within this area develops two weeks earlier in infancy, compared with the capacity to fuse the input from the two eyes when it comes from beyond the horopter (Braddick, 1996). Fusion is more robust within this area because close-up images often involve a considerable viewpoint difference between the two eyes. One thing that is slightly surprising with this behaviour is that the area of the screen is relatively small, compared with the rest of the screen and the whole experimental setting. Note that in the dual-Purkinje eye-tracking apparatus, which typically produces uncrossed fixations, the whole of the set-up is in darkness. The uncrossed fixations in the current study seem to be driven by the relative illumination in a relatively small area around fixation. This is a new finding.

As the participant moves out of region A1 and into region A2, the fixation disparity moves both quantitatively and qualitatively from uncrossed to crossed. The task of reading the numbers is becoming more difficult as the contrast changes to become less pronounced; the screen is also becoming lighter. We expect more crossed fixations here because the illumination level is brighter, but again this is only for a relatively small area of the screen. This local illumination level is closer to normal room lighting conditions. The crossed fixation is optimal for these conditions because the centre of the foveal window consists of the overlap of the two best retina-to-cortex projections—the contralateral projection from each eye: RE to LH and LE to RH. Having a relatively large fixation disparity in these relatively easy reading conditions is optimal because a wider extent of the line is in view and is afforded the best projection conditions—that existing between the two fixation points. In addition, the fact the stimulus in these two areas (A1, A2) is still relatively readable provides an opportunity for binocular adaption to contrast, with evidence of increasing converging binocular behaviours from A1 to A2 and reaching its highest in A2.

As the participant moves into region A3, there is also a rapid change to adapt to the new conditions. It is brighter in this part of the screen and the numbers are becoming impossible to read. The eyes stay crossed, as we would expect from the brightness; the fixation disparity becomes more negative, in terms of our analysis. This seems to indicate a ‘zooming in’ to a particularly very difficult-to-read section of the line. It suggests that there is the capacity to project the critical region between the two fixation points onto a larger area of cortex, so as to increase the chances of being about to discriminate the numbers from the background. The shrinking pupil size in A3 is synchronised with the zooming in process and increasing brightness of the background.

We found generally systematic and continuous effects. Participants necessarily fixated from left to right across the line of the stimulus to read it. To what extent was the binocular fixation

disparity caused by the fact that fixations were to the left or right of space as opposed to the difficulty of reading the stimulus?

In the two studies in Chapters 5 and 6, we see crossed fixations *increasing* in Fig. 5.3 and *decreasing* in Fig. 6.3. This observation leads us to conclude that spatial position is not the determining factor in the two experiments. Contrast at a small spatial scale and overall luminance at a larger spatial scale seem to be the determining factors, even though the reading literature suggests small effects of left-to-right position on the screen (Also see more in the discussion of Chapter 6).

Overall, these adaptive changes are happening quickly as is required in response to the nature of the visual task in a particular part of the line. What is impressive is that these are very peripheral muscle-driven movements of the eyes, but they have adaptive qualitative and quantitative effects in the cortical processing that contributes to cognition. In this sense the cognition is ‘embodied’ in the physical form of the visual system.

The change of these very peripheral muscle-driven movements of the eyes, could also match and reflect the underlying neural modulation in response to contrast. Kuang, Poletti, Victor and Rucci (2012) have argued that fixational eye movements would integrate with the sensitivity of retinal neurons responding to features of visual stimuli. Retinal neural activity has also been suggested to adapt to the statistics produced by visual information (Jarsky et al., 2011), and the process of contrast adaptation could be a cumulative effect modulated by previous processing (Baccus & Meister, 2004). We would then predict high convergence of the binocular fixation in A2 could partially be attributed to the accumulated preparational effect through visual activities in A1.

This potentially synchronised correlation of contrast adaption in visual input from cortical neural circuits to peripheral muscle-driven movements, indicates a systematic and harmonious visual activity showing the flexibility of visual system in different modes of operation. In conclusion, these all suggest the visual adaptative behaviours can synchronise from the basic peripheral binocular movements all the way to higher cognitive processing, in response to the contrast change perceived from stimuli.

There is relatively little research addressed to the way in which the eyes accommodate to gradual changes in the clarity of the stimulus from fixation to fixation across the line. Further studies on this theme might involve replacing the continuous random numbers of the current experiments with coherent single-line text. There can be no useful input from ‘higher cognition’ to the two experiments reported here, as the numbers are not predictable. However, replacing the stimuli with text would allow us to look at participants’ behaviours with respect to predictability. We anticipate a larger proportion of longer saccades and with perhaps more regressive saccades as participants attempt to use foregoing context to disambiguate the unclear words. Such patterns of fixation will potentially reveal how well the preferred viewing location of fixations in words can respond to visual information below the letter-level. Further, providing lexical and sentential contexts should enhance the role of the right hemisphere in ways that are observable.

Chapter 6

Binocular disparity behaviours in a reading-like task with increasingly blurred stimuli

Abstract

In this chapter, we investigate how the visual system reacts and adapts to the level of faintness in a number reading task. In this reading-like task, the text becomes more and more blurred while the background stays bright and white, with increasing blurriness and reading difficulty. We found a considerable increasing distribution of uncrossed binocular fixations as the level of blurriness of the text stimuli increases and reading difficulty increases, though with an overall crossed tendency of binocular fixations. These overall effects suggest a general trend of the reading of blurry stimuli appealing to uncrossed-uncrossed (i.e. uncrossed at the start and end of fixation) binocular adaptative behaviours. These uncrossed patterns facilitate binocular fusion through creating stereo input with better processing at the extremes for higher quality information, through the contralateral advantage. The adaptative binocular performance indicates strategic behaviours of the visual system to optimise visual processing with blurred stimuli.

6.1 Introduction

In Chapter 1, we have discussed the visual system as a whole when responding to blurry stimuli. Previous research found accommodative behaviours in processing blurred text and a difference in binocular movement compared with reading normal nonblurred text. As discussed previously, crossed and uncrossed binocular disparity can represent the response of the two eyes during the viewing process. Jaschinski-Kruza (1994) reports a shift to exophoric (i.e., uncrossed) fixation disparities elicited by increased blurriness of text stimuli. Jainta et al. (2010) also report

adjusted vergence in reading blurry stimuli. Though consistent findings have been reported, they attributed this change of binocular coordination in reading blurry text to the development of fatigue and visual strain.

In this chapter, we conducted a reading-like experiment with carefully designed blurred reading materials with numbers that changed the level of blur as the participant read from the left to the right. We predicted that the binocular behaviours would be modulated based on the level of faintness of the texts and would reveal an adaptative performance. The two eyes would coordinate to accommodate and adjust for better visual quality and performance in different blurred conditions.

6.2 Analysis

Figure 6.1 demonstrates the positions along the digit line where participants are unable to continue reading. We first produced demonstrative graphs to show the distributions of the binocular eye movement behaviours. We then analysed the data quantitatively with GLMER and LMER models, to further characterize the eye-movement behaviours under the specific conditions.

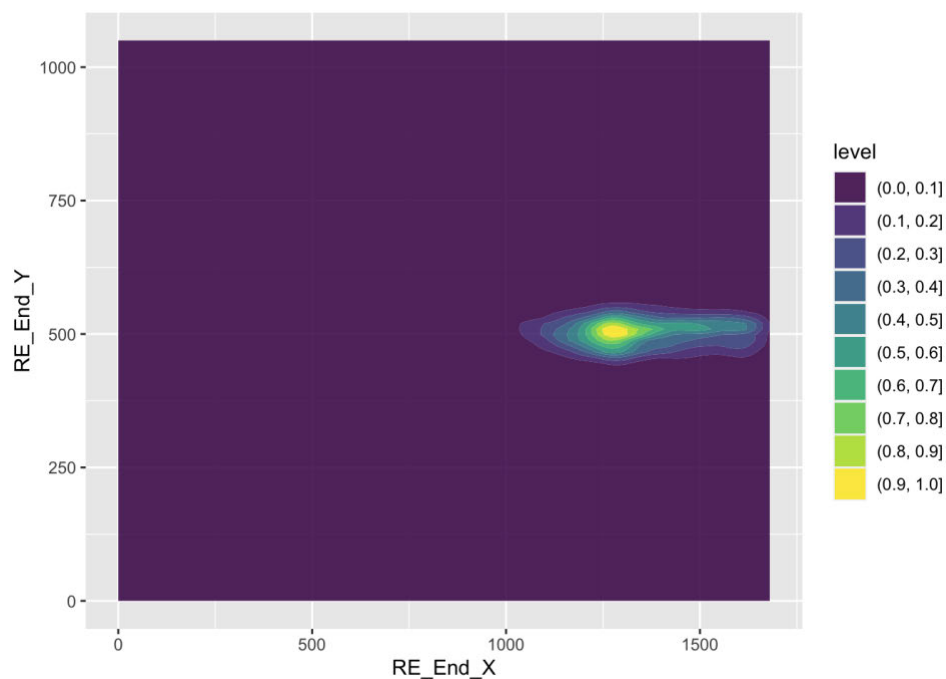


Figure 6.1 The heatmap of locations where the participants find difficult to continue reading.

6.3 Results

We analysed a total of 45,417 binocular fixations in the task. We report the results from two perspectives, together with descriptive statistics and modelling statistics: (a) vergence of the fixation (i.e., convergence vs. divergence); (b) fixation disparity type at the beginning and the end of fixations.

In the modelling results, both Linear Mixed-Effects Regression Models (LMER) and General Linear Mixed-Effects Regression Models (GLMER) were used for quantitative analyses, carried out in R using the lme4 software package (Bates, Maechler, & Dai, 2008). In the GLMER models, we used counts of fixation pairs as dependent variables in the models. We defined null models with participants and some also with trials as random factors depending on the model fit. Predictor variables included the type of vergence during the fixation (convergence, divergence), the type of disparity at the beginning of fixation (crossed, uncrossed) and at the end of fixation (crossed, uncrossed) together as new variables to indicate both, including C-C (i.e. crossed at both the beginning and end of fixation) and U-U (i.e. uncrossed at both the beginning and end of fixation); as well as the horizontal area including the four parts according to the level of faintness (A1, A2, A3, A4 and the viewing difficulty: $A1 < A2 < A3 < A4$). All Model fit was assessed using the anova function to compare models.

6.3.1 Vergence movement in different viewing areas

Figure 6.2 shows the distribution of vergence (convergence, divergence) in different areas (i.e., A1, A2, A3, A4). The reading difficulty increased as participants read from left to right due to the increasing level of faintness from area A1 to A4. The general distribution shows a relatively high distribution of convergence in binocular fixations within the two most visible areas (A1 and

A2) compared with the difficult reading areas (A3 and A4). Specifically, the distribution from A1 to A2 shows an increasing distribution of convergence and reaches the peak in A2 among all areas. In contrast, this trend of convergence starts to decrease from A3 and reaches the lowest proportion of convergence in A4. Table 6.1 further shows the statistical significance of the increase of convergence in A2 and decrease in A3 and A4, compared with A1.

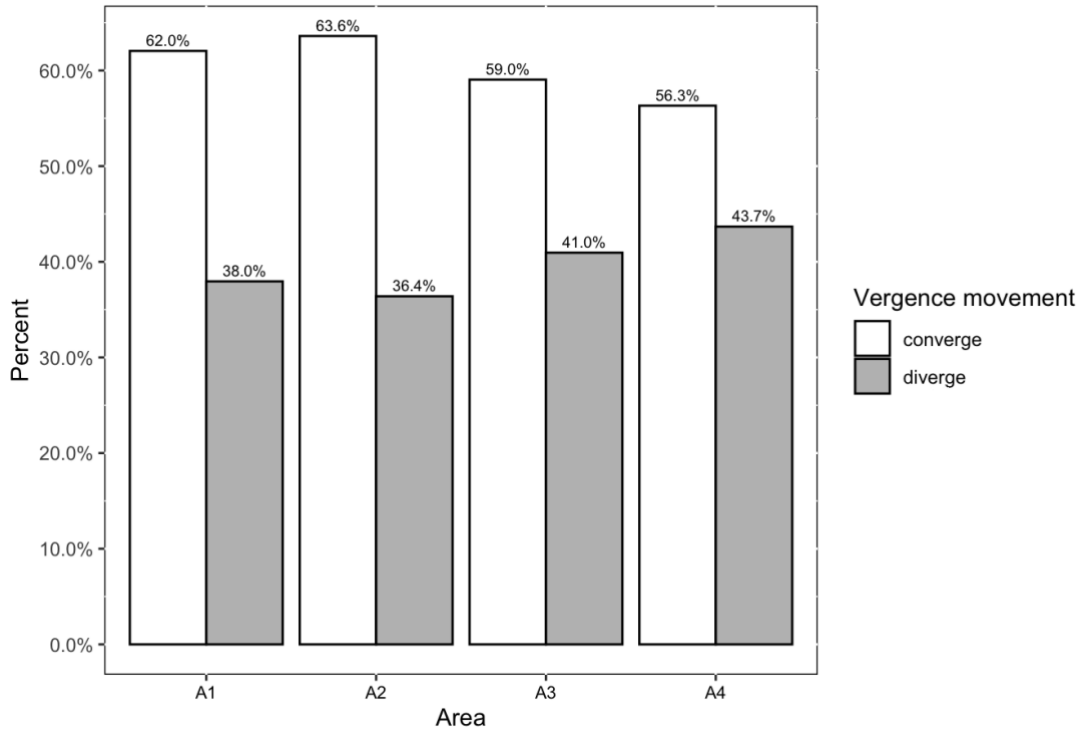


Figure 6.2 The distribution of vergence in each viewing area. A2 shows highest convergence distribution among all.

The number of fixations		
	null model	vergence*area
	(1)	(2)
A2		-0.147 (<0.001)
A3		0.261 (<0.001)
A4		0.300 (<0.001)
converge	0.404 (<0.001)	0.492 (<0.001)
A2:converge		0.067 (0.014)
A3:converge		-0.126 (<0.001)
A4:converge		-0.237 (<0.001)
Constant	4.895 (<0.001)	4.775 (<0.001)
Random effects		

Participant(38)	Variance 0.1065	Std.Dev. 0.3263
Observations	304	304
Log Likelihood	-6,974.019	-6,524.339
Akaike Inf. Crit.	13,954.040	13,066.680
Bayesian Inf. Crit.	13,965.190	13,100.130

Note: p value in parentheses.

Table 6.1 *GLMER analysis of distribution of vergence in each viewing area*

6.3.2 Disparity type at the beginning and end of fixation

Figure 6.3 shows the type of disparity at the beginning and end of fixations, with crossed (C) and uncrossed fixations (U). Two types—both the beginning and the end as crossed fixations (C-C) and both as uncrossed fixations (U-U)—are the dominant fixation types. Whereas the crossed type of fixation (C-C) decreased gradually, though it was the most frequent type, the overall uncrossed fixation type (U-U) shows an increasing number, as participants read from A1 to A4. The comparison of A1 and A4 as the easiest and the hardest area to read shows the greatest difference.

Statistical models with two main areas (A1, A4) and types (C-C, U-U) from Table 6.2 further supported the difference of this distribution in the disparity type at the beginning and end of fixation in each area (A1 and U-U as references). Similar to the descriptive analysis, the model shows significantly more uncrossed-to-uncrossed fixations (U-U) values in the area of A4, compared with reading in A1.

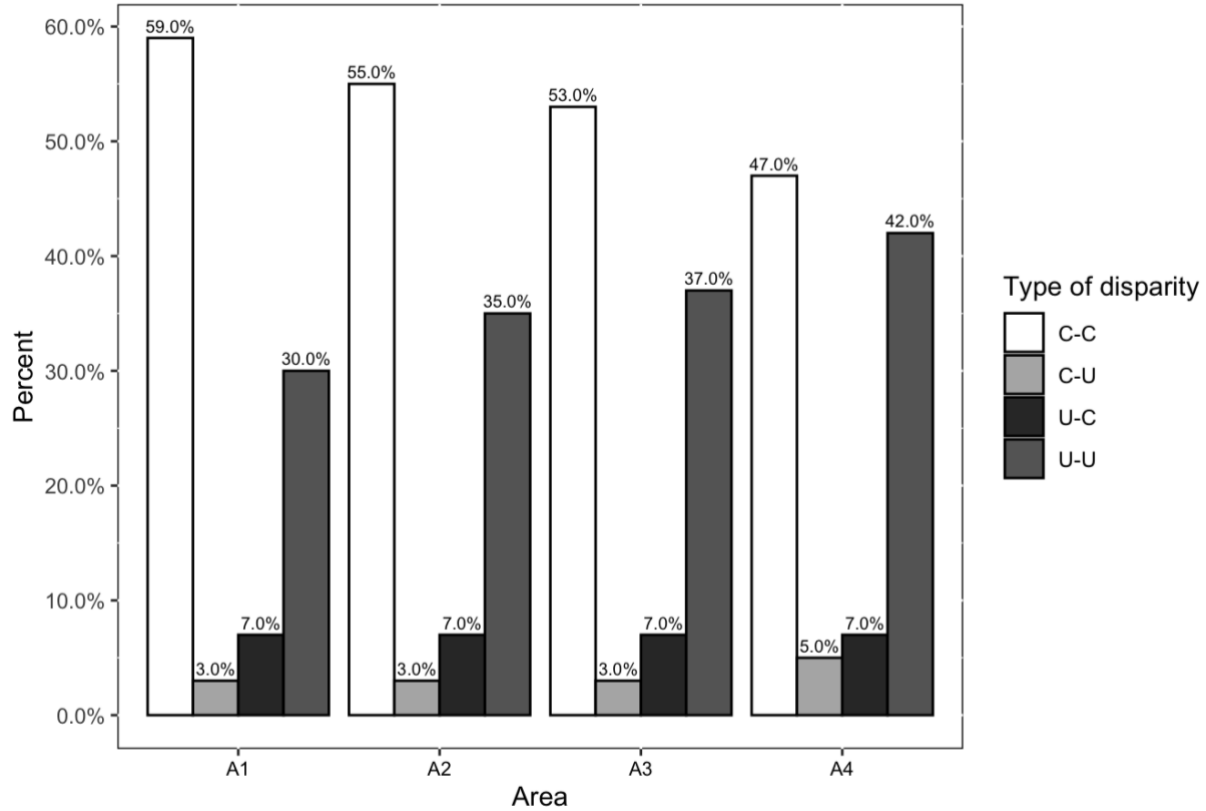


Figure 6.3 The distribution of disparity type at the beginning and end of fixations.
Crossed-Crossed disparities show predominance in all areas.

	The number of fixations	
	(1)	(2)
	No interaction	disparity*area
A4	0.156 (<0.001)	-0.121 (<0.001)
U-U	0.221 (<0.001)	-0.596 (<0.001)
A4:U-U		0.692 (<0.001)
Constant	4.831 (<0.001)	5.193 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	0.2462	0.4962
Observations	141	141
Log Likelihood	-8,704.914	-8,368.516
Akaike Inf. Crit.	17,417.830	16,747.030
Bayesian Inf. Crit.	17,429.620	16,761.780

Note: p value in parentheses.

Table 6.2 GLMER analysis of distribution of disparity types in the viewing area

6.4 Discussion

We found a considerable increasing distribution of uncrossed fixation pairs as the level of blurriness of the text stimuli increases and reading difficulty increases, though with an overall crossed tendency of binocular fixations. The binocular movement effect based on vergence becomes relatively highest in the second lowest blurry area (A2), suggesting a potential binocular adaptation through its disparity change in response to blurriness of the text. The lowest level of blurriness area (A1) shows the greatest proportion of crossed fixations. The quantitative change of the fixation disparity type shows a systematic change, with decreasing crossed fixations and increasing uncrossed fixations. The area with the highest level of blurriness (A4) generates the highest percentage of uncrossed fixations. These overall effects suggest a general trend of the reading of blurry stimuli appealing to uncrossed-uncrossed binocular adaptative behaviours.

Figure 6.2 shows a marginally significant increase in convergence between A1 and A2. There is a corresponding decrease in divergence. This pattern is to be interpreted as the most frequent response of modern humans attending to close work and looking at things that are easily within their reach—to converge on a close object. When we stop attending closely to things, the eyes diverge. However, it is a strategy that cannot work for these stimulus materials, because the stimuli themselves are blurred and cannot be improved upon. Nevertheless, this is the first strategy that the participants adopted to improve the quality of the visual information that needs to be fused from both eyes.

Convergence means in some instances that the two fixation points are becoming more nearly conjugate. We assume that exactly conjugate fixation points are advantageous. In other instances, convergence produces crossed fixations. We assume crossed fixations are advantageous; the quality of visual information is best in the contralateral projection from left eye to right hemisphere

and from right eye to left hemisphere (Toosy et al., 2001; Shillcock et al., 2010), so the visual information falling *between* the two crossed fixation points receives the best processing possible. This latter case is the general explanation for the fact that C-C fixations predominate overall in the data.

Previous studies have shown that uncrossed fixations reflect difficult reading conditions that could create a challenge for binocular fusion, such as a dark visual environment for the dual-purkinje eye-tracker (Shillcock et al., 2010) and a dark reading background (Kirkby et al., 2013). A similar rapid qualitative change has previously been anecdotally observed in a laboratory setting during the reading of text, elicited by a switch to a lower room lighting level (Shillcock et al., 2010).

Participants' behaviour moving from A1 to A4 shows a strategy. The strategy is a response to the stimuli becoming even harder to read. Figure 6.3 shows a clear decrease in the proportion of C-C fixations and a corresponding increase in U-U fixations. This new strategy reflects the fact that nothing the visual system can do can improve the quality of the visual information. The best it can do is resort to the strategy it normally adopts when processing is very hard and unpredictable. This strategy involves diverging and bringing the plane of the stimulus within the horopter, that is, between the horopter and the participant, as the best strategy when everything else is not working. It allows the visual system to completely reject the input from one eye or the other, as is necessary when what is being inspected is very close and the visual system cannot get a good overlapping fused image because the entity is just too close.

This adaptation does not improve processing in the current case, but it is the strategy the system resorts to when drastic action needs to be taken. It doesn't improve the quality of the visual processing because ipsilateral projections are being employed—right eye to right hemisphere and

left eye to left hemisphere. However, as the divergence gets larger the area between the two fixation points increases, so a larger field of foveal processing comes into play, possibly giving the processor some advantage in looking for continuity and context in the visual stimulus. Because of the nature of the stimuli, none of these strategies can eventually succeed completely.

There is considerable variation between participants in this experiment. This variation is to be expected, given that participants were presented with stimuli that, towards the right of the screen, could not be read at all and which mimicked perceptions caused by faulty vergence or by faulty accommodation. Our analysis is based on different strategies adopted by the participants as they attempt to optimise processing on any one fixation. Overall percentages of different binocular behaviours are therefore the most insightful data to consider.

We found generally systematic and continuous effects. Participants necessarily fixated from left to right across the line of the stimulus to read it. To what extent was the binocular fixation disparity caused by the fact that fixations were to the left or right of space as opposed to the difficulty of reading the stimulus?

First, we can exclude a spatial effect that has been an important artefact for vision research based on cathode-ray tube presentations (García-Pérez & Peli, 2001) in which the screen itself emitted more light on the right; the current studies used non-CRT technology.

In reading studies, one early study (Heller & Radach, 1999) shows fixation disparity increasing when participants read the first line of multi-line text. In later work (Liversedge, White et al., 2006) the size of end-of-fixation disparity was quite stable across the sentence/screen, but with larger proportions of crossed fixations at the two ends of the screen. Nuthmann and Kliegl (2009, Fig. 6) present single-line reading data from the Potsdam Corpus; these data were recorded using binocular calibration and so should be interpreted with care—the relative size of the

binocular disparity will be more trustworthy than any absolute data. The very first fixations on each line should also be interpreted with care, given the unorthodox presentation of the stimulus with respect to the fixation of the starting stimulus (the authors were aiming to simulate continuous reading at the start of the line. However, their data show a flat distribution across the x-axis for the relative frequency of uncrossed binocular fixation disparities; the crossed fixation disparities show a slight (@5%) increase in the proportion of crossed fixations at the end of fixation, but it is difficult to interpret this increase given that the authors' binocular calibration procedure assumes an initial conjoint fixation. Overall, though, the authors claim that binocular fixation disparity accumulates during the course of successive saccades and fixations along a line of text.

In summary, the data are scant on this issue, but they do suggest that the binocular fixation disparity in reading accumulates over the left-to-right passage across the screen. In Nuthmann and Kliegl's study's the fixations are mostly crossed fixations, while in our findings there are increasing uncrossed fixations. Therefore, position is unlikely to be the determining factor in the two experiments. Finally, cognitive load has provided somewhat mixed outcomes regarding binocular fixation disparity. Juhasz et al. (2006) report no effect, but see Heller and Radach (1999).

Overall, our findings are consistent with the results reported by Jaschinski-Kruza (1994), where increased blurriness of text stimuli cause a shift to an exophoric (i.e. uncrossed) fixation disparities. Shillcock et al. (2010) also suggest that uncrossed patterns of fixations tend to reflect relative difficulty of stereofusion during reading. Contrary to Jainta et al. (2011), the uncrossed-uncrossed pattern shows a strongly presented systematic increase when the text stimuli become very hard to read due to the increased level of blur, which could not be attributed to fatigue or the visual strain of reading.

It may be that the U-U strategy partly emerges because it matches the situation of very near viewing (or sighting), when only one eye provides a useful image and the other eye's input requires to be suppressed. In the current case, *neither* eye is in fact providing anything like a good input.

Overall, we see that the strategies appear in a predictable way between the different levels of blurring. These behaviours are not induced by fatigue but by the fixation-to-fixation nature of the stimulus. Therefore, in this experiment, the emergence of the uncrossed-uncrossed behaviours facilitates the viewer in making comparisons across a larger field of view. When the characters are getting harder to read because successive sections are becoming blurrier, the uncrossed-uncrossed fixation behaviour puts the best, contralateral processing to the left and right of the viewing window, with the slightly less good visual processing in the middle. The uncrossed patterns also potentially facilitate binocular fusion through creating stereo input with the better processing at the extremes, through the contralateral advantage of the left eye's input projected to the RH and the right eye's input projected to the LH. The viewing window created by the specific binocular behaviours of dense uncrossed fixations, could potentially benefit visual processing when a whole object (a line of text, or a particular section of the line of text) needs to be perceived, especially in the difficult viewing part, therefore providing higher quality information by more effective fusion of the binocular input. The eyes are adapting different strategies to try to optimise visual processing with blurred stimuli.

We also suggest that we might follow up anecdotal observations from the current thesis, in which we expect to see differences in the *vertical* relationship between fixation and the stimulus. Blurred or faint visual stimuli are often the outcome of inadequate accommodation by the lens, resulting from inappropriate depth focusing. This may have implication for the respective roles of absolute and relative disparity processing, as part of depth processing; such processing differs

between the dorsal and ventral pathways and may suggest interpretations of differences in vertical fixation on the stimuli, with the upper and lower hemifields being differentially projected along the visual pathways, which will be discussed more specifically in Chapter 8.

Chapter 7

Spheres and the illusion of depth

Abstract

In this chapter, we investigate how the visual system reacts and responds to a visual illusion created by depth information as a cue for judgement of perceived size. In particular, we used two spheres of the same size, perceived differently due to their background (Murray et al., 2006), under two viewing conditions (i.e. each sphere at a different time; two spheres together) and analysed participants' vergence behaviours. We found opposite results from two different viewing tasks. The results indicate the responses by the two eyes to the illusion of depth and only partially support Murray et al.'s (2006) interpretation of their data. It further implies the illusion reaches into the higher cortical regions of visual processing not just to the primary visual cortex, and all the way out to the very peripheral processing responsible for vergence.

7.1 Introduction

In chapter one, we have discussed Murray et al.'s (2006) experiment with far and near spheres as well as the possible change of eye-movement behaviours to adapt to far and near objects under natural viewing conditions. In this chapter, we will replicate their spheres experiment (cf. also Kersten & Murray, 2010) and explore binocular eye movements in viewing illusional depth perception stimuli. The general question to explore here is: are there any eye-movement behaviours that differ between viewing the 'near' and 'far' spheres and can we interpret them in terms of this preparation for active engagement with the objects of the world?

What happens when we look at a near or far sphere? In the real world of near and far objects we diverge to fixate on the far sphere and we converge to fixate on the near sphere. These vergence movements will be accompanied by changes in the lens and the pupil to bring the respective objects at different distances into focus (Patterson, 2015). In the stimulus materials containing the illusion, the two spheres are at the same distance and if one is in focus the other will also be in focus—there is no physical depth, but rather there is perceived depth in the picture. The differences we are looking for are all in terms of vergence movements.

In the experiment we carried out, we explored the eye-movements that might be expected to accompany the viewing of such an illusion. Can those eye movements shed light on the visual processing? Might they explain the data concerning the larger area of VI activated in the illusion (Murray et al., 2006)? Murray et al. interpret their finding to mean that the illusorily larger size of the ‘far’ sphere is actually manifested as a correspondingly larger area of activation in V1; that is, the illusion is ‘real’ in VI—the ‘far’ sphere really is larger.

However, if there is a large disparity between the fixation points of the two eyes, then this will create a larger area of activation of V1, because the relevant areas occupied by the image on the two retinas will not precisely correspond in any retinotopic representation combining the images from the two eyes.

The conventional, idealized assumption is that the two lines of sight from the eyes intersect on the surface of the object; the horopter is the curved 3D surface that contains the fixation point and all the other points in space at which the content of the two eyes’ fixations fall on ‘corresponding points’ on the two retinas. (Vojnikovi & Tamajo, 2013).

We studied the process of moving the eyes between the two locations and inspecting an identically sized sphere in each position, through an eye-tracking experiment. We manipulated the

task in ways that might affect the experience of the illusion and that also might elicit different eye-movement behaviours, namely by requiring subjects (a) to fixate a single visible sphere in either location and (b) by requiring subjects to move back and forwards between two coexisting spheres in the two locations.

We test two key hypotheses. We predict (1) that the 2D representation of depth will elicit vergence behaviours that are coherent with looking at real-world differences in depth. (We ignore lens and pupil behaviours.) That is, we predict that the illusion will ‘work’ at the level of eye movements. In particular, we predict more convergence (and convergence that turns from uncrossed into crossed fixations) for viewing the ‘near’ sphere. Note that the interaction of visual illusions and eye movements is relatively unexplored, so any different behaviours elicited by different tasks within the set of stimuli will be particularly instructive.

We predict (2) vergence movements corresponding with fixating the ‘near’ and ‘far’ sphere will produce more divergence and greater fixation disparities at the ‘far’ sphere. Such greater fixation disparity will suggest that the binocular retinotopic projection of the fixated ‘far’ sphere will occupy a larger area of V1—an alternative explanation for Murray et al.’s data. N.B. As we discuss later, Murray et al. were aware of this possibility but dismissed it.

7.2 Analysis

We first produced demonstrative graphs to show the distributions of the disparity-related features of eye movements. We then analysed the data quantitatively with GLMER and LMER models, to further characterize the eye-movement behaviours during the specific tasks.

7.3 Results

We analysed a total of 3852 binocular fixations in the Sphere 1 task and 14690 binocular fixations in the Sphere 2 task. Below, we first report descriptive statistics from three perspectives: (a) sphere position and vergence during the fixation; (b) disparity type at the beginning in both spheres positions and tasks; (c) change of fixation disparity for all sphere positions and tasks. Then, we report the quantitative analysis from GLMER and LMER models from three perspectives: (a) vergence types and their interaction with sphere position and sphere task; (b) disparity types and their interaction with sphere position and sphere task; finally LMER models with (c) change of fixation disparity in sphere position and the two types of task.

7.3.1 Descriptive results

7.3.1.1 Vergence type during the fixation

Figure 7.1 shows the distribution of disparity (i.e., convergence and divergence) at the front and back sphere, respectively, in the Sphere 1 task. Convergence is defined as the right eye fixation moving leftwards and/or the left eye fixation moving rightwards. Dominant distribution of convergence fixation pairs can be seen at the front sphere, whereas this proportion changed at the back sphere, with more diverging data and less converging ones.

On the other hand, in Figure 7.2, the disparity at the front and back sphere in the Sphere 2 task shows greater differences in distribution. The dominance of convergence appears at both front and back spheres. This predominance is even greater at the back sphere.

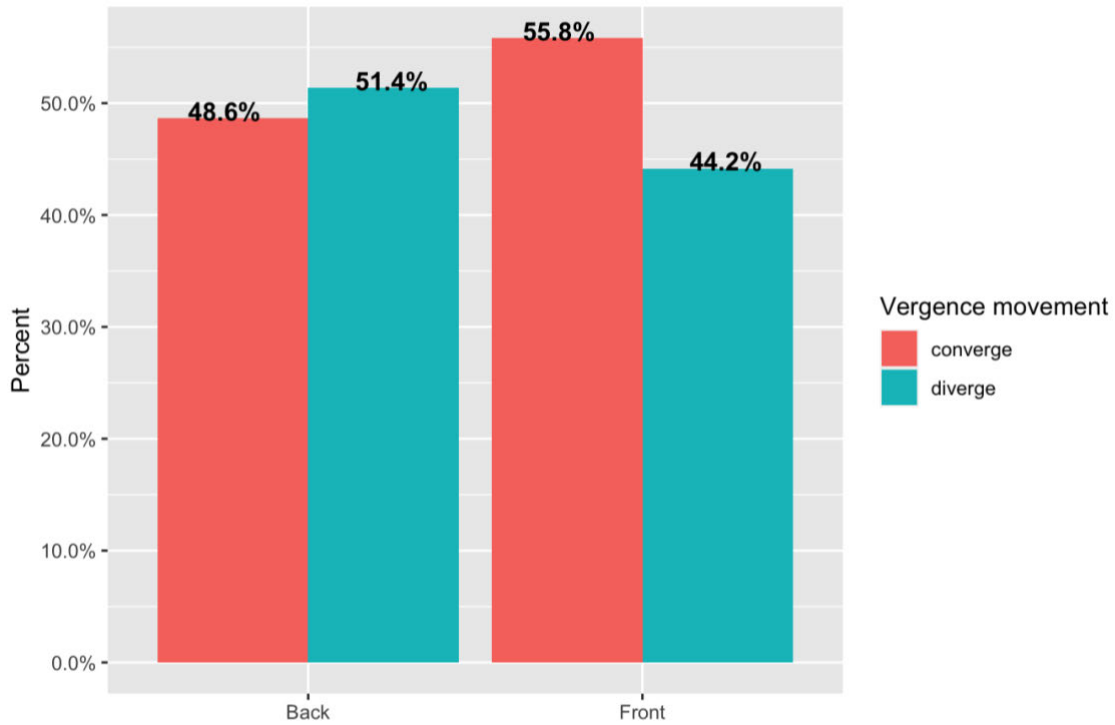


Figure 7.1 The distribution of disparity in the Sphere 1 task.

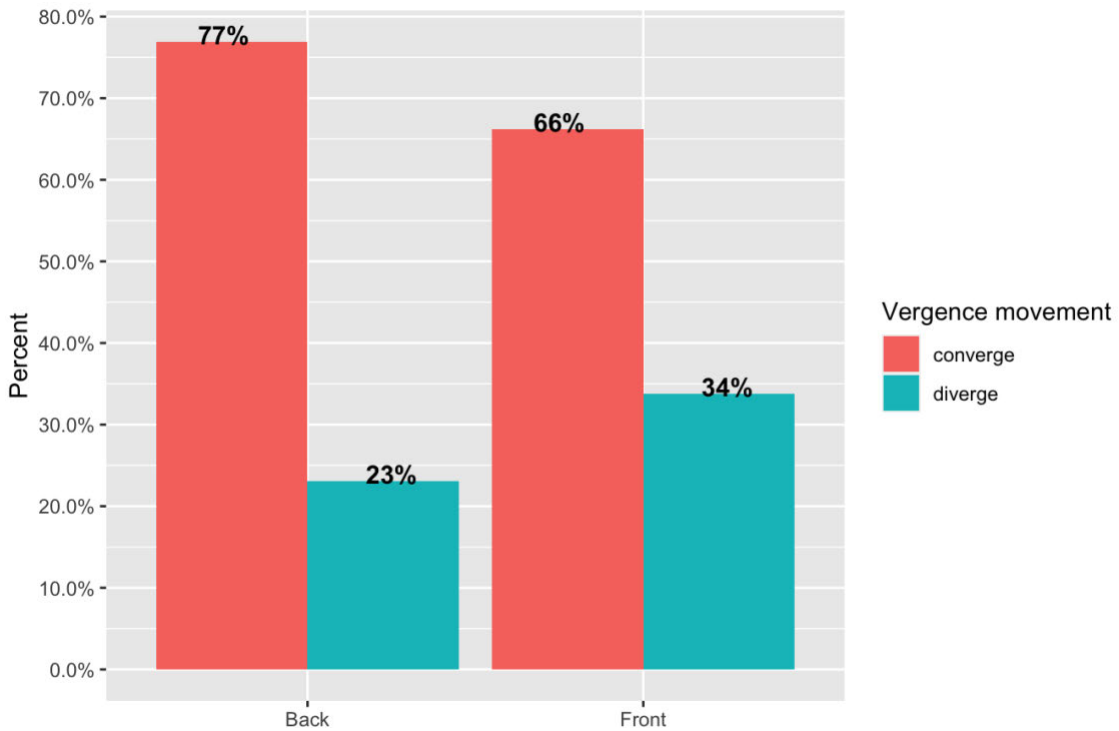


Figure 7.2 The distribution of disparity type in the Sphere 2 task.

The distributions of vergence movements in the two tasks are different in appearance, suggesting effects of the task. Convergence predominates overall only in Sphere 2. In both tasks there appears to be an interaction between vergence type and location of fixation.

Figure 7.3 shows the disparity differences between the Sphere 1 and Sphere 2 tasks. Sphere 2 shows a greater imbalance between convergent and divergent fixations, with predominantly converging fixations, compared with Sphere 1, which shows just slightly more converging fixations.

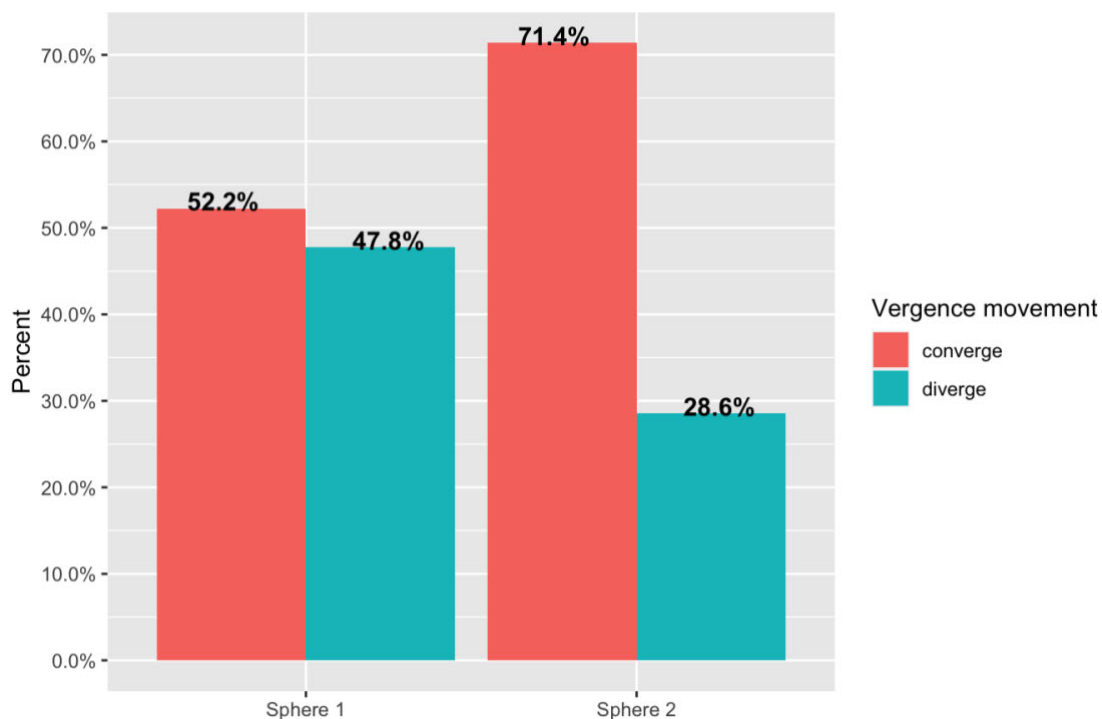


Figure 7.3 *The distribution of disparity type in both Spheres 1 and 2 tasks. There appears to be an effect of task type on vergence behaviours.*

7.3.1.2 Disparity at the beginning of fixation

Figures 7.4 and 7.5 show the distribution of disparity types at the beginning of fixation in the Sphere 1 and 2 tasks respectively. The beginning of fixations in both spheres tasks indicate the binocular onset in each task at the ‘front’ and ‘back’, which is defined by the position on

the horizontal axis of the right eye minus that of the left eye. More crossed than uncrossed fixation pairs at the beginning can be observed at both back and front, in both Spheres 1 and 2 tasks. The distribution of crossed fixations shows greater differences in Sphere 2 between the front and back, with more at the front; while the difference is quite narrow in Sphere 1, with just slightly more at the back. In terms of uncrossed fixations, the results are also opposite in the two tasks. Whereas there is a slightly higher distribution at the front sphere in the Sphere 1 task, they appear more at the back sphere in Sphere 2.

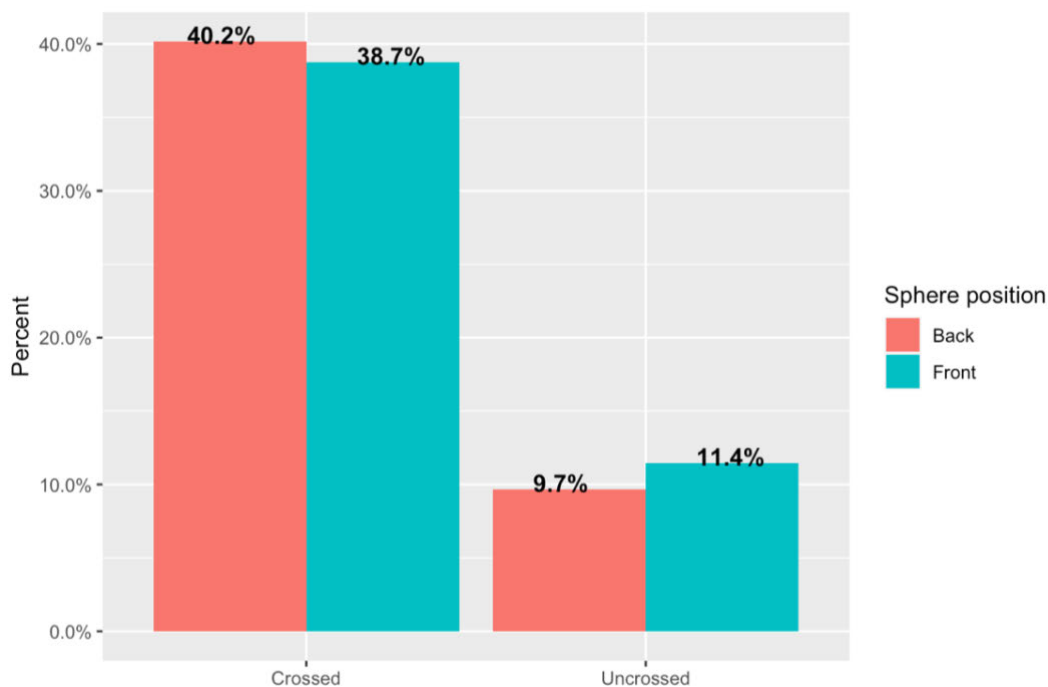


Figure 7.4 *The distribution of disparity at the beginning of fixation in the Sphere 1 task. The location of fixation appears to produce similar distributions of crossed and uncrossed fixation disparities.*

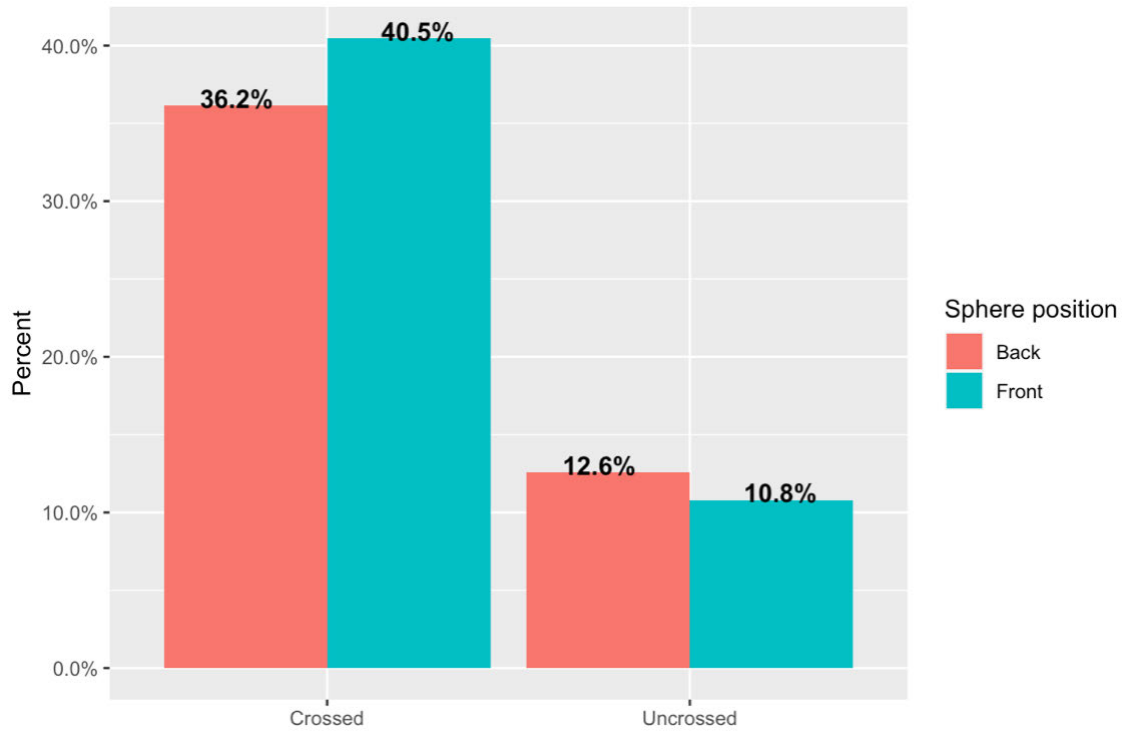


Figure 7.5 *The distribution of disparity at the beginning of fixation in the Sphere 2 task. The location of fixation again appears to produce similar distributions of crossed and uncrossed fixation disparities.*

7.3.1.3 Change of fixation disparity

Figure 7.6 shows the change of disparity within the fixations in both spheres tasks at the back and front respectively. The change of disparity means how the disparity changes from the start to the end of fixation, which is the disparity of fixation pairs at the end of fixation minus the disparity at the beginning. It can be seen that the peak of distribution in the Sphere 1 task goes to the centre zero, whereas that in the Sphere 2 task is positioned at the left side of zero, which means that the peak is in the area of negative value. The negative peak distribution in the Sphere 2 task indicates the result of uncrossed fixation pairs becoming crossed or crossed pairs becoming more crossed, i.e., the tendency of binocular fixations to converge in Sphere 2.

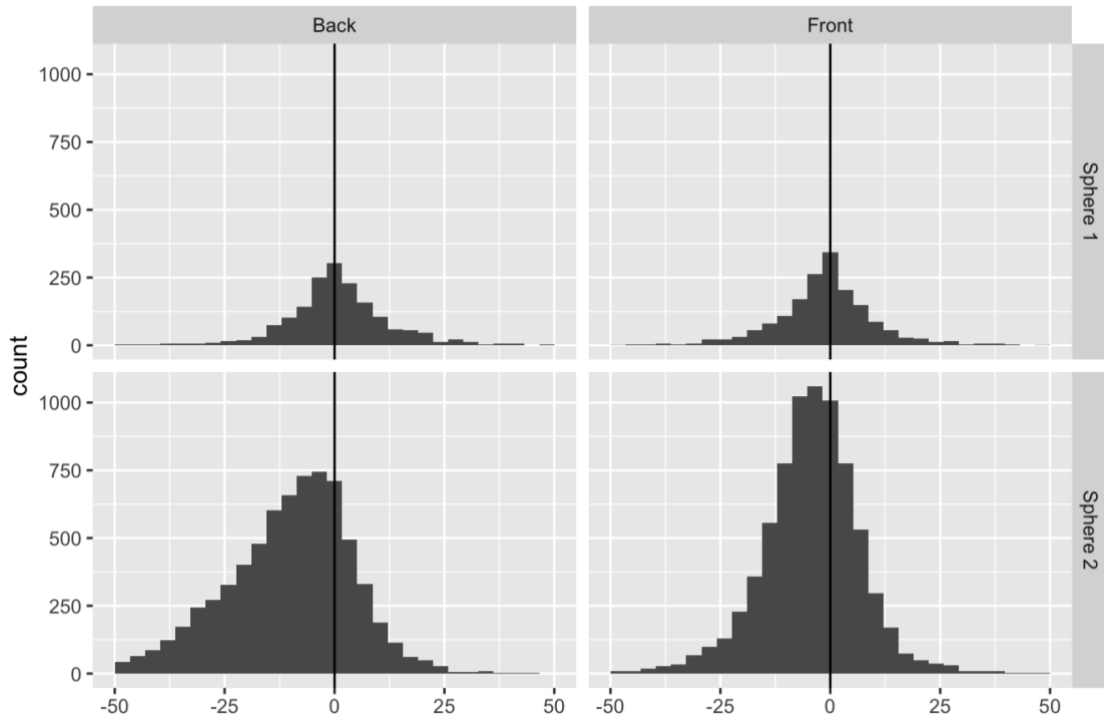


Figure 7.6 *The change of disparity in the fixation at back and front spheres in both spheres tasks. The location of fixation appears to produce similar distributions of crossed and uncrossed fixation disparities.*

7.3.2 Modeling results

Both Linear Mixed-Effects Regression Models (LMER) and General Linear Mixed-Effects Regression Models (GLMER) were used for quantitative analyses, carried out in R using the lme4 software package (Bates, Maechler, & Dai, 2008). In the GLMER models, we use counts of fixation pairs as dependent variables in the models. We defined null models with participants and trials as random factors. Predictor variables included the directional type of disparity during the fixation (convergence, divergence), the qualitative type of disparity at the beginning of fixation (crossed, uncrossed), the position of the sphere (front, back) and the type of task (Sphere 1, Sphere 2). In the LMER models, we use the change of disparity (i.e. the disparity at the end of fixation minus the disparity at the beginning) as the dependent variable in the models. We defined null models with participants as random factors. Predictor variables

included the position of the sphere (front, back) and the type of task (Sphere 1, Sphere 2). All Model fit was assessed using the anova function to compare models.

7.3.2.1 Vergence type during the fixation

Results from GLMER models show that the counts of convergence fixation pairs are significantly more than diverging fixations in both spheres tasks, 1 and 2, which is in accordance with Figures 7.1 and 7.2. In the Sphere 1 task, an only marginally significant value of the predicted diverging fixations at the back sphere can be seen in Table 7.1. However, we find significantly more convergence at the back sphere in the Sphere 2 task, as shown in Table 7.2, which is the opposite of the predicted result in the Sphere 1 task. This different result in Sphere 1 and Sphere 2 tasks can be further analyzed in the model shown in Table 7.3, which shows in general, significantly more values of converging fixation pairs in the Sphere 2 task, which is in accordance with Figure 7.3.

	The number of fixations vergence (1)	sphere position*vergence (2)
Back		-0.080 (0.091)
Diverge	-0.135 (<0.001)	-0.215 (<0.001)
Back:Diverge		0.160 (0.002)
Constant	0.513 (<0.001)	0.551 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(35)	0.0372	0.1931
Observations	2,102	2,102
Log Likelihood	-2,888.960	-2,886.251
Akaike Inf. Crit.	5,783.920	5,782.502
Bayesian Inf. Crit.	5,800.872	5,810.755

Note: p value in parentheses.

Table 7.1 The interaction between Sphere position and disparity in the Sphere 1 task

	The number of fixations	
	vergence (1)	sphere position*vergence (2)
Back		-0.346 (<0.001)
Converge	0.716 (<0.001)	0.538 (<0.001)
Back:Converge		0.398 (<0.001)
Constant	2.403 (<0.001)	2.553 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(35)	0.0645	0.2541
Trial(4)	0.0010	0.0321
Observations	837	837
Log Likelihood	-5,044.201	-4,980.375
Akaike Inf. Crit.	10,096.400	9,972.750
Bayesian Inf. Crit.	10,115.320	10,001.130

Note: p value in parentheses.

Table 7.2 The interaction between Sphere position and disparity in the Sphere 2 task

	The number of fixations	
	vergence (1)	sphere task*vergence (2)
Task2		2.030 (<0.001)
Converge	0.590 (<0.001)	0.142 (<0.001)
Task2:Converge		0.569 (<0.001)
Constant	0.518 (<0.001)	0.382 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	0.0388	0.1969
Trial(24)	0.0006	0.0248
Observations	2,939	2,939
Log Likelihood	-8,245.795	-8,075.328
Akaike Inf. Crit.	16,499.590	16,162.660
Bayesian Inf. Crit.	16,523.530	16,198.570

Note: p value in parentheses;

Table 7.3 The difference of vergence movement between Sphere 1 and Sphere 2 tasks

7.3.2.2 Disparity at the beginning of fixation

	The number of fixations	
	disparity (1)	sphere position*disparity (2)

Back		-0.153 (0.044)
Crossed	0.064 (0.196)	-0.023 (0.714)
Back:Crossed		0.183 (0.033)
Constant	0.395 (<0.001)	0.467 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(35)	0.0377	0.1944
Observations	2,102	2,102
Log Likelihood	-2,895.857	-2,893.572
Akaike Inf. Crit.	5,797.714	5,797.143
Bayesian Inf. Crit.	5,814.666	5,825.396

Note: p value in parentheses;

Table 7.4 *The interaction between sphere position and disparity type at the start of fixation in the Sphere 1 task*

	The number of fixations	
	disparity (1)	sphere position*disparity (2)
Back		-0.074 (<0.001)
Uncrossed	-0.261 (<0.001)	-0.355 (<0.001)
Back:Uncrossed		0.186 (<0.001)
Constant	2.919 (<0.001)	2.955 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	0.0504	0.2246
Trial(4)	0.0008	0.0292
Observations	837	837
Log Likelihood	-5,788.159	-5,775.434
Akaike Inf. Crit.	11,584.320	11,562.870
Bayesian Inf. Crit.	11,603.240	11,591.250

Note: p value in parentheses;

Table 7.5 *The interaction between sphere position and disparity at the start of fixation in the Sphere 2 task*

Table 7.4 and 7.5 show the disparity at the beginning of fixation in the Sphere 1 and 2 tasks respectively. The slightly more crossed data at the back sphere in the Sphere 1 task shown in Figure 7.6—which is counter to predictions—is not statistically significant, as presented in Table 7.4. However, the predicted greater number of uncrossed fixations at the beginning are significant at the back sphere in the Sphere 2 task, as can be seen in Table 7.5.

7.3.2.3 Change of disparity in the fixation

	The change of disparity	
	null model	sphere position
	(1)	(2)
Back		2.163 (<0.001)
Constant	0.453 (0.530)	-0.622 (0.424)
Random effects		
	Variance	Std.Dev.
Participant(35)	13.84	3.721
Trial(20)	0.3314	0.5757
Observations	3,430	3,430
Log Likelihood	-14,738.270	-14,731.450
Akaike Inf. Crit.	29,484.550	29,472.910
Bayesian Inf. Crit.	29,509.110	29,503.610

Note: p value in parentheses;

Table 7.6 *The difference between sphere position in disparity change in the Sphere 1 task*

	The change of disparity	
	null model	sphere position
	(1)	(2)
Back		-6.999 (<0.001)
Constant	-7.315 (<0.001)	-3.879 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	17.28	4.157
Observations	14,547	14,547
Log Likelihood	-60,419.670	-60,033.010
Akaike Inf. Crit.	120,845.300	120,074.000
Bayesian Inf. Crit.	120,868.100	120,104.400

Note: p value in parentheses;

Table 7.7 *The difference between sphere position in disparity change in the Sphere 2 task*

The change of disparity in the Sphere 1 task, as shown in Table 7.6, is associated with significant positive value at the back sphere, which indicates the tendency of crossed fixation pairs to become uncrossed or become less crossed, i.e., to diverge, as predicted. The results in Sphere 2 show negative change at the back sphere compared with the front in terms of disparity, as can be seen in Table 7.7, indicating the tendency of binocular fixations to converge, in accordance with Figure 7.6—and counter to predictions. In addition, the difference between Sphere 1 and 2 tasks

in the change of disparity can be further analyzed through the model shown in Table 7.8. The change in the Sphere 2 task shows significantly greater negativity compared with that in Sphere 1, which is in accordance with the significantly greater value for convergence in Table 7.3. This change at the back sphere indicates even greater negative change of disparity in Sphere 2 with a significant converging tendency in the binocular fixations.

	The change of disparity	
	sphere position	sphere task*sphere position
	(1)	(2)
Sphere task2		-2.392 (<0.001)
Back	-5.227 (<0.001)	2.010 (<0.001)
Sphere task 2:Back		-8.973 (<0.001)
Constant	-3.469 (<0.001)	-1.536 (<0.05)
Random effects		
	Variance	Std.Dev.
Participant(38)	12.79	3.576
Observations	17,977	17,977
Log Likelihood	-75,320.900	-74,960.620
Akaike Inf. Crit.	150,649.800	149,933.200
Bayesian Inf. Crit.	150,681.000	149,980.000

Note: p value in parentheses;

Table 7.8 *The interaction between sphere position and sphere task 1 and 2 in disparity change*

7.4 Discussion

This experiment was an exploration. Could we contribute to the theory of visual processing by eye-tracking participants as they perceived visual illusions? Specifically, we addressed Murray et al.'s (2006) claim that an illusorily larger stimulus corresponds to a larger area of activation in the primary visual cortex.

In the Sphere 1 task, one sphere was visible at a time, which participants fixated. In the Sphere 2 task, participants alternately fixated two spheres present at the same time.

By default, we assumed similar convergence responses to perceived depth in the two tasks.

We predicted, first, that the perceived depth would cause more divergence at the 'far' sphere, moving the intersection of the lines of sight to fixate more distantly. Participants would perceive 2D 'depth' similar to real depth.

We predicted, second, that there would be non-trivial fixation disparity at the 'far' sphere. If this disparity is greater than at the 'near' sphere, it raises a question about Murray et al.'s interpretation of the larger V1 retinotopic activation of the illusorily larger 'far' sphere. The striations of the primary visual cortex correspond to alternating projections from the individual eyes. A fixation disparity (i.e., a non-exact overlap of the two monocular images of the 'far' sphere) means a larger total area of activation in V1 across the total contributions from the two eyes.

The first, general conclusion we draw is that eye-tracking the perception of 2D stimuli representing 3D relations is a complex endeavour that yields rich data and suggests a number of future constraints on tasks and stimuli.

Did participants perceive the 2D depth as real depth consistently throughout both experiments? We make the same assumptions as Murray et al. in this respect. They report, in supplementary data, that there is indeed variation between participants. There is no means within the technology or the procedure of the experiment to know the extent to which participants were perceiving the whole stimulus scene as opposed to selectively attending to the green fixation points on the spheres (as also used by Murray et al.) and potentially reducing the effects of the overall scene. We note that Fang, Boyaci, Kersten and Murray (2008) show that selective attention to a central fixation target can reduce the size of an illusion that they infer is represented in the retinotopic activation in V1 (in this later study, they employed a different illusion from the spheres illusion).

Differences between participants' behaviours in the two tasks in the current data most likely reflect differences in selective attention to the fixation targets on the spheres. Note also that the Sphere 2 experiment produced almost four times more fixations overall than the Sphere 1 experiment, again a potential source of differential behaviour.

There are hemispheric differences regarding depth perception—see our study of the perception of Plateau's Spiral in a later chapter. It may be that further experimentation reveals that the illusion is best experienced when the critical parts of the stimulus are projected primarily to one or other hemisphere. At this point, it is not possible to predict which hemisphere would be most susceptible to the illusion—the right hemisphere, which deals in the authentic appreciation of depth, or the left hemisphere, which prefers not to process the experience of depth.

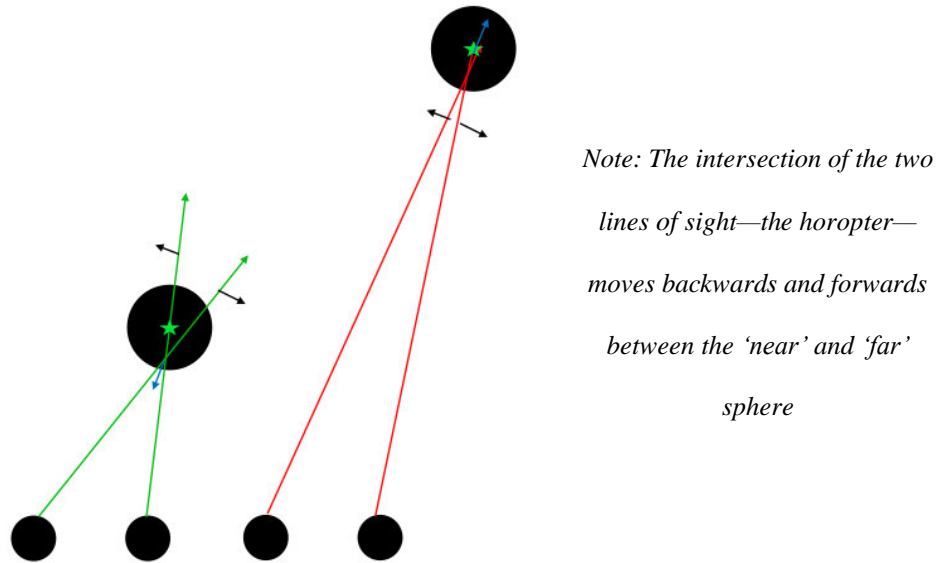


Figure 7.7 The two lines of sight move backwards and forwards between the 'near' and 'far' targets in sphere task 1.

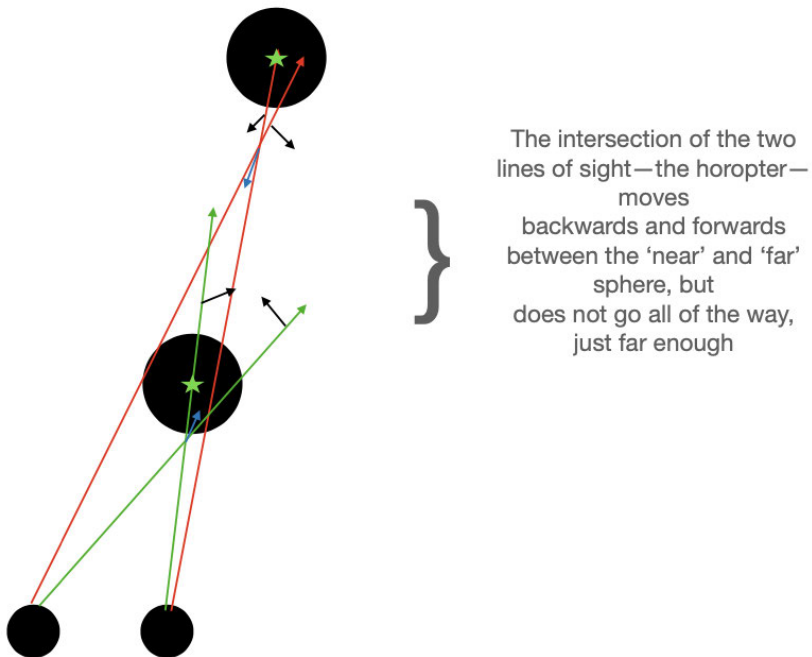


Figure 7.8 The two lines of sight move backwards and forwards between the 'near' and 'far' targets in sphere task 2.

In the Sphere 1 task (Fig. 7.1 & 7.7), viewers converged their lines of sight when viewing the ‘near’ sphere. This behaviour had the effect of bringing the horopter closer to the viewer, as if viewing a nearby object. In contrast, they diverged their lines of sight when looking at the ‘far’ sphere, thereby moving the horopter farther away, as if viewing a distant object. This pattern of behaviour was as predicted; it was only marginally significant in our modelling of the data.

In the Sphere 2 task, convergence predominated (fig. 7.2 & 7.8). The significantly greater convergence at the back sphere was counter to our predictions: participants converged as if fixating a *near* as opposed to a *far* target.

At this point in the analysis, what the two spheres experiments have shown is that viewers’ fixation behaviours reflect the nature of the task and the nature of the 2D representation of 3D perspective. In this respect, the Sphere 1 results extend to a new stimulus and a new task, previous findings showing binocular behaviours being caused by 2D representation of depth (cf. Both et al., 2003; Enright, 1987a; Enright, 1987b; Ringach, 1996; Sheliga, 2003). The Sphere 1 results reflect a straightforward visual interpretation of the 2D scene in 3D terms.

The Sphere 2 results showing significantly more convergence for the back sphere show that task requirements can reverse the behaviours that we expect from the 2D representation of 3D perspective, and which we saw in the Sphere 1 task.

We looked at the distribution of crossed and uncrossed fixation disparities. Our default assumption was that there should be more crossed fixations for a ‘near’ target and more uncrossed fixations for a ‘far’ target.

Fig. 7.4 shows the reverse of this prediction, in the Sphere 1 task: more uncrossed at the front, more crossed at the back. Our modelling showed these differences not to be significant.

Fig. 7.5 shows the distribution of fixation disparities to be in line with our assumption, in the Sphere 2 task: more crossed at the front and more uncrossed at the back. Our modelling shows this greater number of uncrossed fixations at the back sphere in the Sphere 2 task to be significant.

Fig. 7.6 shows the changes in fixation disparity within fixations. It is a key result with respect to Murray et al.'s claim (see below) that differential overlap of the retinotopic projections from the two eyes is not responsible for the overall larger size of the representation of the 'far' sphere in V1. This result shows a wider distribution of changes in disparity for the 'far' sphere in the Sphere 2 experiment. Note that these changes are more revealing than the qualitative differences crossed vs uncrossed. A crossed fixation can become even more crossed, increasing the size of the disparity (and representing a larger non-overlap of the two retinotopic images in V1. Table 7.8 supports the statistical significance of this difference.

At this point in the analysis, we see a symmetrical relation between the directions of behaviour in the two tasks. In Sphere 1, the vergence behaviour is as assumed—tending to diverge to fixate an apparently far object; but the fixation disparities are contrary to predictions—more uncrossed fixations at the apparently near target. In Sphere 2, the opposite pattern obtains: the vergence behaviour is contrary to prediction—tending to converge to fixate an apparently far object; but the fixation disparities are as predicted—more uncrossed fixations at the apparently far target. Not every aspect of this relation was statistically significant, but we suggest it offers the best interpretation to be pursued in further work.

In Sphere 1, the depth illusion works for the vergence behaviour. Participants had to move fixation to the green dot which preceded a single sphere's appearance. They fixated the 'near' sphere first, then the 'far' sphere, diverging to fixate the apparently more distant sphere. Because the 'near' sphere was always fixated first, we can make no real predictions about the direction of

fixation disparity in this first fixation; it is still visually interpretable as being some distance away from the viewer and in any case the modelling showed that the differences in direction of fixation disparity were not significant for this task.

We suggest that in the Sphere 2 condition, planning a saccade to the other sphere's green fixation point is a task of selective attention and differs critically from what was required in the Sphere 1 condition. Attention has to be moved from one sphere to the other. We speculate that the 2D representation of 3D depth and perspective was weakened or eliminated (cf. Fang et al., 2008). There was a significant effect of convergence but it was in the reverse direction to the default prediction; the convergence was greatest at the 'far' sphere. At this point, all we can do is speculate that this paradoxical effect of convergence for an apparently far target may represent a compensation of some kind for the apparent depth. This effect must remain the subject of further empirical investigation.

We provisionally exclude the possibility that differential fixation behaviours were caused by the fact that the 'near' sphere was lower on the screen than the 'far' sphere, because we see opposite behaviours between Sphere 1 and Sphere 2 experiments.

Murray, Boyaci and Kersten (2006) appear to make the common assumption that the two eyes fixate exactly conjointly; they do not say anything to the contrary. We know there is typically some fixation disparity (Liversedge et al., 2006) and that even very small fixation disparities can have qualitative effects in terms of depth perception (Hibbard et al., 2017). Murray et al. report that the behavioural effects of the size illusion were qualitatively very robust over several measurement techniques, in which duration of viewing and presence of one or both spheres was varied. They further state (Murray et al., 2006), in a Supplementary Note to their 2006 paper:

“Vergence eye position and binocular viewing. Differences in vergence eye position could result in slight changes in the distribution of activity in V1 and a previous study has shown that monocular depth cues can cause changes in vergence eye movements. In other words, in the presence of 2D depth cues the ocular-motor system can behave as if it is viewing an actual 3D scene. Though this previous study used a different depth cue (kinetic depth effect, KDE), could similar vergence differences have occurred when subjects were observing the front and back spheres in our experiment? We feel that this possibility is extremely unlikely. A necessary condition in the KDE experiments was that the stimuli were viewed monocularly. When the experiments were repeated with binocular vision, the modulation in vergence was completely absent. The authors note that this is not surprising given that very small changes in vergence (20 min arc) would cause diplopia.”

The study they refer to is Ringach, Hawken and Shapley’s (1996) study concerning vergence movements in response to the Kinetic Depth Effect. We have shown that this effect does in fact occur and with stimuli taken from Murray et al.’s study.

In summary, I have shown: (1) Visual illusions, such as the size illusion we have investigated, can have behavioural effects at the level of eye movements and fixation behaviours.

(2) Different tasks involving a size illusion can have quantitatively and qualitatively different outcomes in terms of binocular fixations.

(3) Murray et al.’s apparent VI correlate of the size illusion may be partially attributable to larger binocular fixation disparities at the ‘far’ sphere.

In conclusion, I suggest, first, that this experiment only partially supports Murray et al.’s interpretation of their data; the apparently larger area activated in VI by the illusorily larger sphere

could possibly be due to sizeable non-overlap between the retinotopic mappings from the left and right eye, resulting from greater fixation disparity on the ‘far’ sphere.

Second, the implications of the illusion are not confined to the higher cortical regions of visual processing, nor to just the primary visual cortex. Rather, the implications go all the way to the very peripheral processing responsible for vergence. The vergence behaviour itself is a response to higher-order processing.

The stimuli in the spheres experiment already contained a limited representation of real-world information, in the form of visual cues to depth perception; the spheres appear in a picture of a brick-lined corridor. Further studies might productively reduce or increase the real-world content. Reduction could be achieved by simplifying the depth cues by taking out the texture cues created by the bricks and the shadows. An increase in the real-world cues could be brought about by using AR technology to situate the reader within the virtual world.

AR technology allows the experimenter to manipulate the monocular images projected to each eye. It potentially allows qualitatively greater control of the image stimuli than is possible with prisms or with existing haploscope technology or with shutter goggles. AR technology allows us to investigate vergence behaviours in stimuli such as those used in this experiment when the stimulus is only projected to one or other eye, or to one or other hemisphere. Such a paradigm would provide unparalleled insights into monocular or binocular information that drives vergence behaviours. Overall, the study of illusion perception using eye-movements, let alone AR technology, can profitably be advanced by studying different visual illusions.

Chapter 8

Spirals and a visual illusion

Abstract

In this chapter, we investigate binocular adaptative processing of the visual illusion elicited by viewing a challenging visual stimulus, Plateau's Spiral (cf. Wade & Heller, 2003). It includes the two directions of motion, clockwise and anticlockwise. We found general similarities in processing the two types of spirals, but a remarkable difference in the binocular strategies in processing different spatial positions. It shows a concentration in the lower centre in vertical processing, and a clear difference horizontally with predominantly crossed fixations at the left and uncrossed at the right of the centre. The results show that the direction of fixation disparity changed according to whether the input directed the largest part of the stimulus to the left (LH) or right (RH) hemisphere. It all indicates hemispherical projection and specialisation during viewing an illusionary stimulus and the corresponding binocular strategies for visual processing.

8.1 Introduction

In Chapter 1, we have seen that our visual system is sensitive to motion perception in illusions, especially the orientation of the movement. Research on rotation and visual motion processing has gained a lot of interest and has been conducted mainly on motion aftereffects and the principles of the 'visual coding' in visual system (Wainwright, 1999). In addition, we also discussed the binocular control of the visual system and its potential to react and respond to different visual stimuli to obtain higher quality processing.

Little has been explored about the adaptation and adjustment of the visual system *during* visual motion processing, in terms of hemispherical projection and the coordination of binocularity. How would the two eyes respond to stimuli that produce a motion-based illusion, given that such stimuli produce not just an aftereffect but different perceptions *during* the stimulus? Below, we investigate the binocular features of vergence control and fixation disparity, in viewing a visually challenging stimulus, Plateau's Spiral (Wade & Heller, 2003).

Here we explore eye movement control by instructing participants to view the centre of the screen, when the illusion associated with a spiral appears. The general question to explore here is: are there any eye-movement behaviours that differ when viewing clockwise and anticlockwise spirals and how would the visual system benefit from any division of labour between the two eyes?

We predict that: (1) The apparent movement of the spiral will produce different vergence responses depending on the clockwise or anticlockwise direction of the spinning of the spiral. We predict that the visual system will respond to the illusion induced by the direction of the motion, clockwise and anticlockwise, given that the illusion causes different perceptual effects *during* viewing of the stimulus;

(2) Participants will employ a division of labour between the two eyes, such that one eye is fixating more accurately, or more adaptively, and the other eye is 'catching up', as in the effects reported by Enright (1998) and Cornell, and Macdougall, Predebon and Curthoys (2003). We expect to see, typically, the right eye moving more predictably in the direction of movement of the contours of the spiral. The right eye's behaviour may vary, responding more on the right side of the screen; perhaps ocular dominance and ocular prevalence combine for the right eye.

We also predict (3) Participants viewing the disturbing spiral illusion will seek to minimize their discomfort by tending to fixate *below* the centre of the spiral, which will project the key part

of the stimulus to the ventral visual pathway as opposed to the dorsal visual pathway (cf. Clark, 2009). In the last two decades and before, the dorsal pathway has been claimed to be concerned with spatial attention, spatial scaling, and magnitude estimation (e.g. Buetti & Walsh, 2009; Fias, Lammertyn, Reynvoet, Dupont & Orban, 2003; Parton, Malhotra & Husain, 2004). Speculatively, it will therefore be more disturbed by the illusion, compared with the ventral stream, which is more concerned with matching the visual stimulus against stored templates. Participants prefer less disturbance.

8.2 Analysis

We first produced demonstrative graphs to show the distributions of the binocular eye movement behaviours. We then analysed the data quantitatively with GLMER and LMER models, to further characterize the eye-movement behaviours under the specific conditions.

8.3 Results

We analysed a total of 3178 binocular fixations in the Clockwise spiral and 3340 binocular fixations in the Anticlockwise spiral, with 6518 in total. During the viewing of the spirals, though instructed to view at the centre, the fixations of the participants drifted to different directions, demonstrating potential influence of the spiral illusion, therefore, eye-movement behaviours under different spatial positions is included. Below, we first report descriptive statistics from two perspectives: (a) vergence during the fixation for both spirals; (b) disparity type of both spirals under different spatial positions (i.e., left, right, up and down). Then, we report the quantitative analysis from GLMER models from three perspectives: (a) vergence movement and the interaction with the horizontal and vertical distribution respectively; (b) disparity type and the interaction with

spatial distribution; (c) division of labour between the two eyes, with the absolute horizontal movement during the fixation of the two eyes in both spirals.

8.3.1 Descriptive results

8.3.1.1 General spatial distribution of the fixation

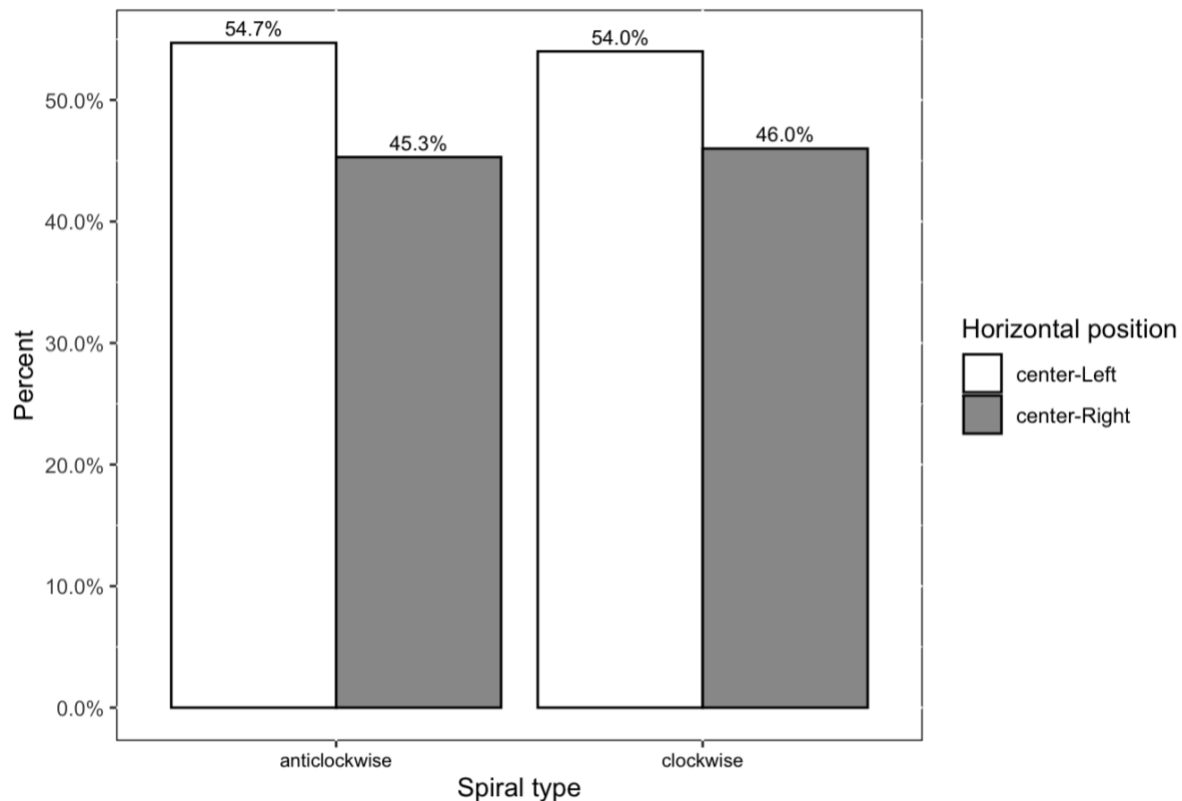


Figure 8.1 Horizontal distribution of fixations in both spirals.
Similar concentration can be found at the centre-left for both types of spirals.

Figures 8.1 and 8.2 show the general spatial distribution of fixations in both spirals, horizontally (i.e., left and right of the spiral's centre) and vertically (i.e., up and down) respectively. Both spirals show very similar results in both horizontal and vertical distribution. The horizontal distribution of the binocular fixations in both spirals shows more concentration to the left of the centre, compared with the right. Both spirals also show a similar vertical distribution, with a striking difference between above and below the centre. A greater concentration of the fixations

can be seen below the centre in both spirals, with over 65% of fixations distributed at below the centre.

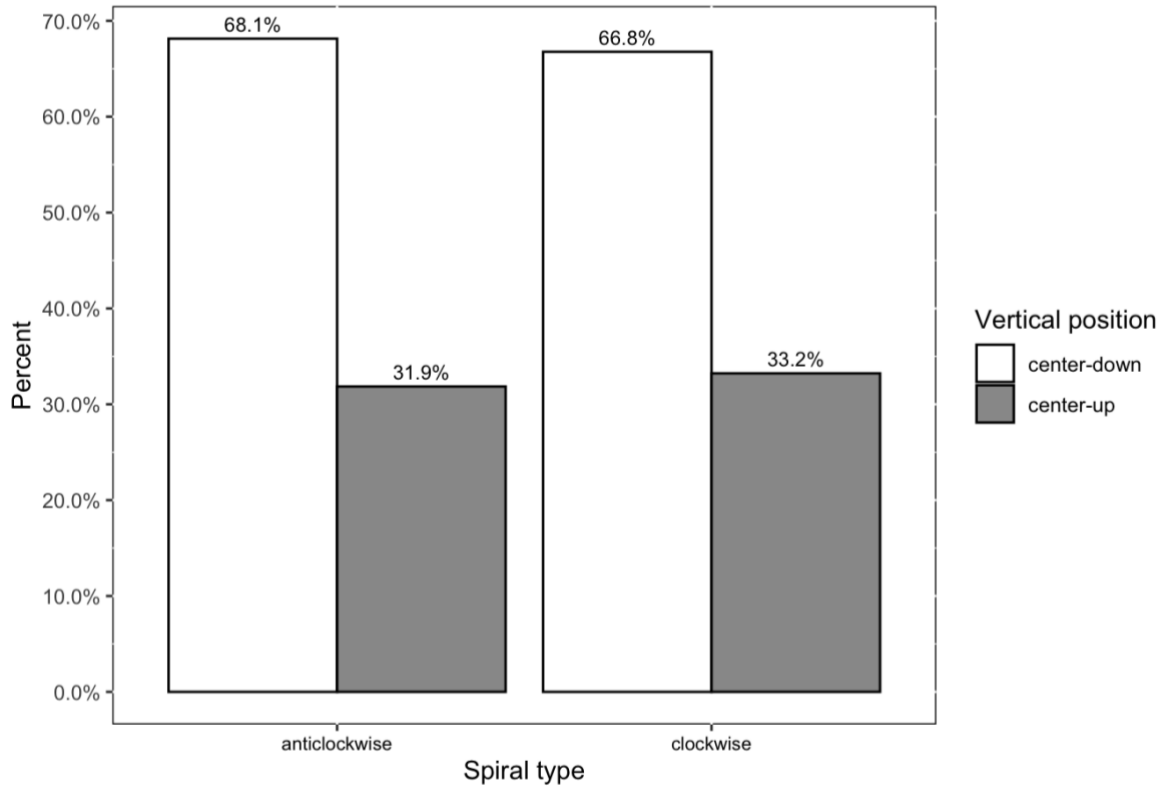


Figure 8.2 Vertical distribution of fixations in both spirals.
Similar concentration can be found at the centre-down for both types of spirals.

8.3.1.2 Vergence type during the fixation

Figure 8.3 shows the distribution of vergence (i.e., convergence and divergence) in the clockwise and anticlockwise spirals. Convergence is defined as the right eye fixation moving leftwards and/or the left eye fixation moving rightwards. A predominant distribution of converging fixations can be seen in both spirals, but with a less marked difference in viewing the anticlockwise spiral.

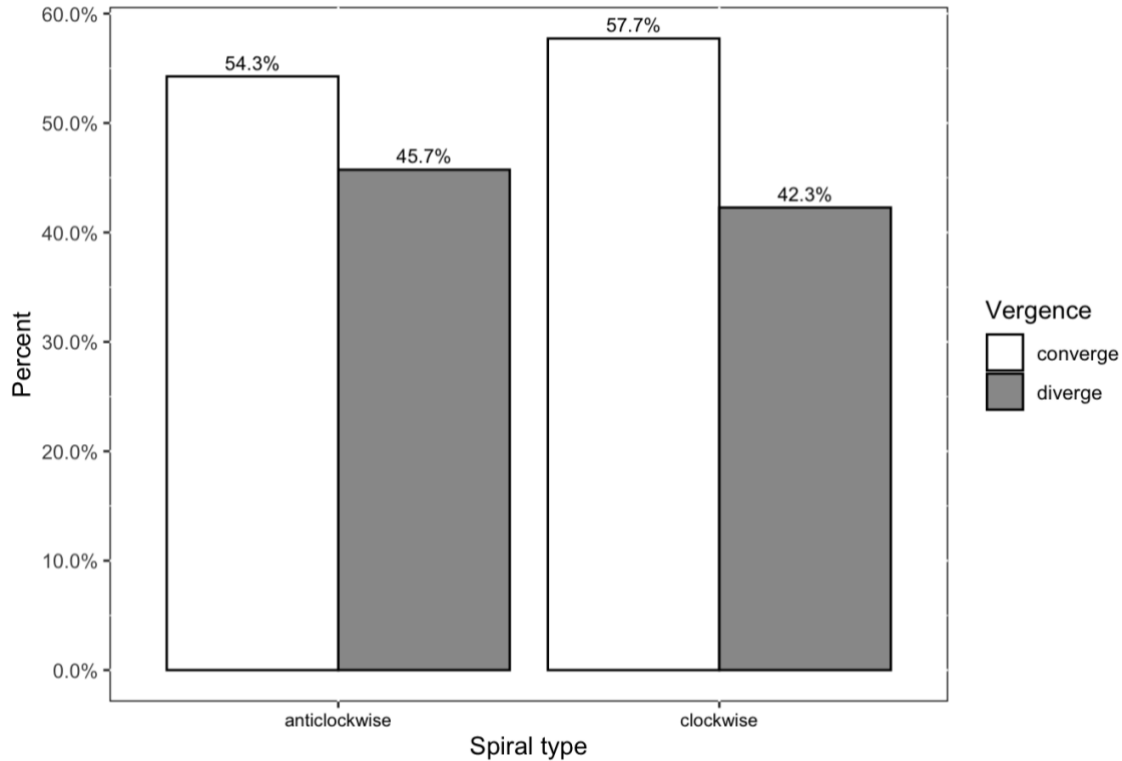


Figure 8.3 *The general distribution of vergence type in both spirals. More convergence than divergence in both spirals. Anticlockwise shows slightly higher distribution of divergence.*

Figures 8.4 and 8.5 further show the vertical and horizontal distribution of vergence type in the two spirals respectively. In the horizontal distribution presented in Figure 8.4, converging binocular fixations show higher concentration at the left of centre in the clockwise condition, whereas the distinction between converging and diverging is less marked in the centre left and centre-right fixations in the anticlockwise spirals.

In addition, the vertical distribution of vergence types in Figure 8.5 demonstrates consistency with the general vertical distribution in Figure 8.3. Both spirals show greater concentration in convergence binocular fixations as well as slightly higher distribution at the upper centre for both conditions, comparatively.

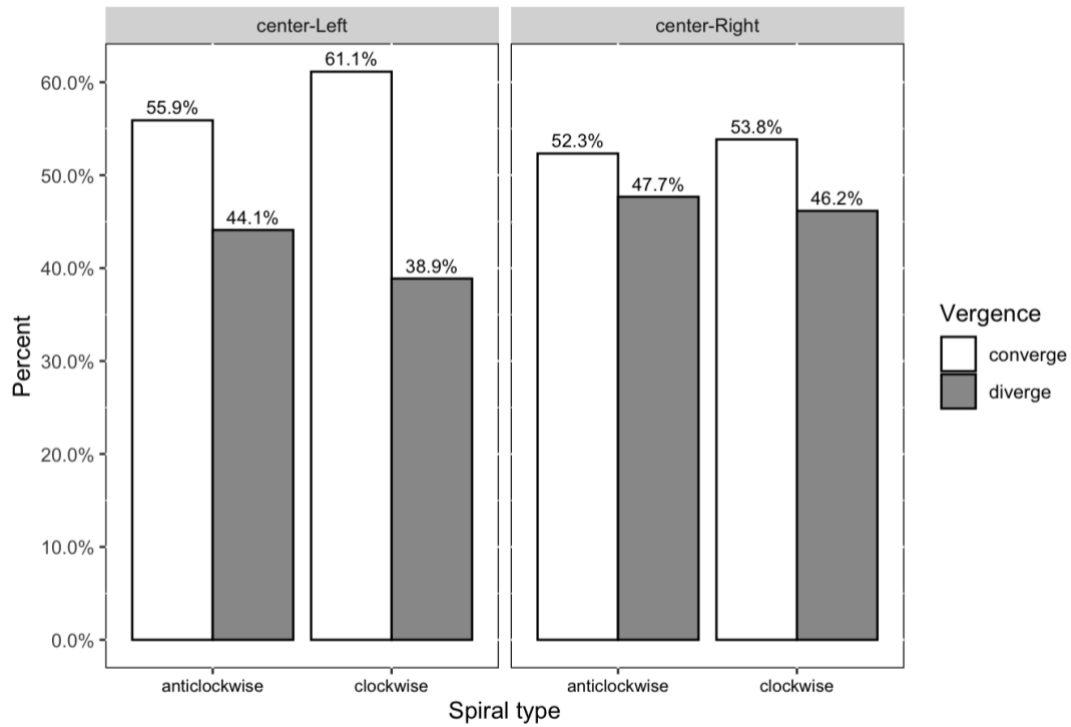


Figure 8.4 Horizontal distribution of vergence type in both spirals. Slightly greater concentration shows at centre-left of clockwise spiral.

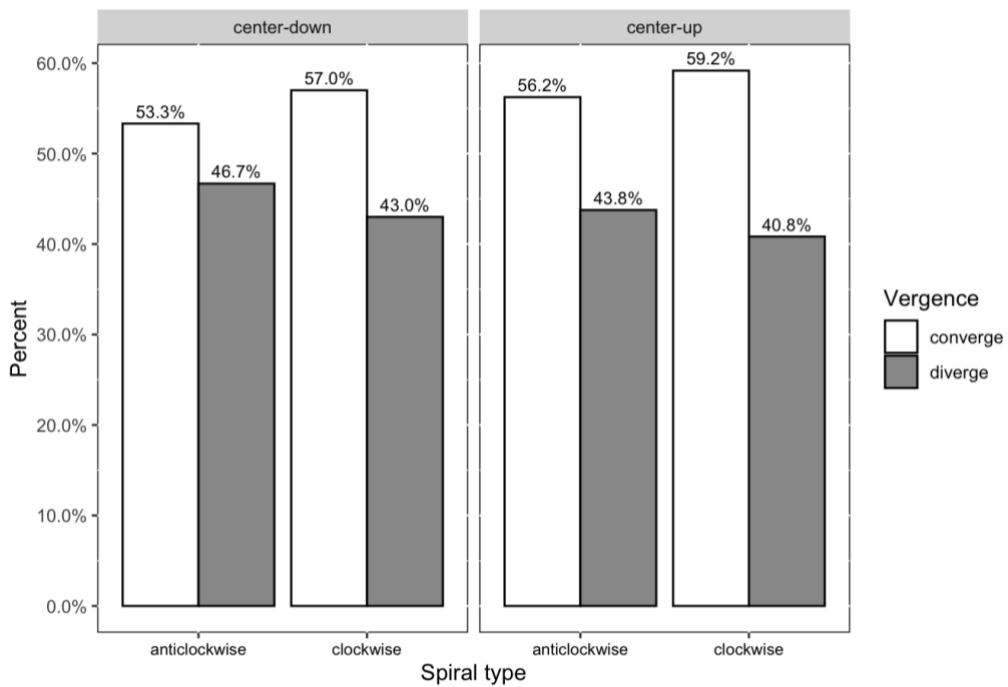


Figure 8.5 Vertical distribution of vergence type in both spirals. Slight higher distribution of convergence can be found for fixations at centre-up, compared to centre-down in both conditions.

8.3.1.3 Disparity type of the fixation

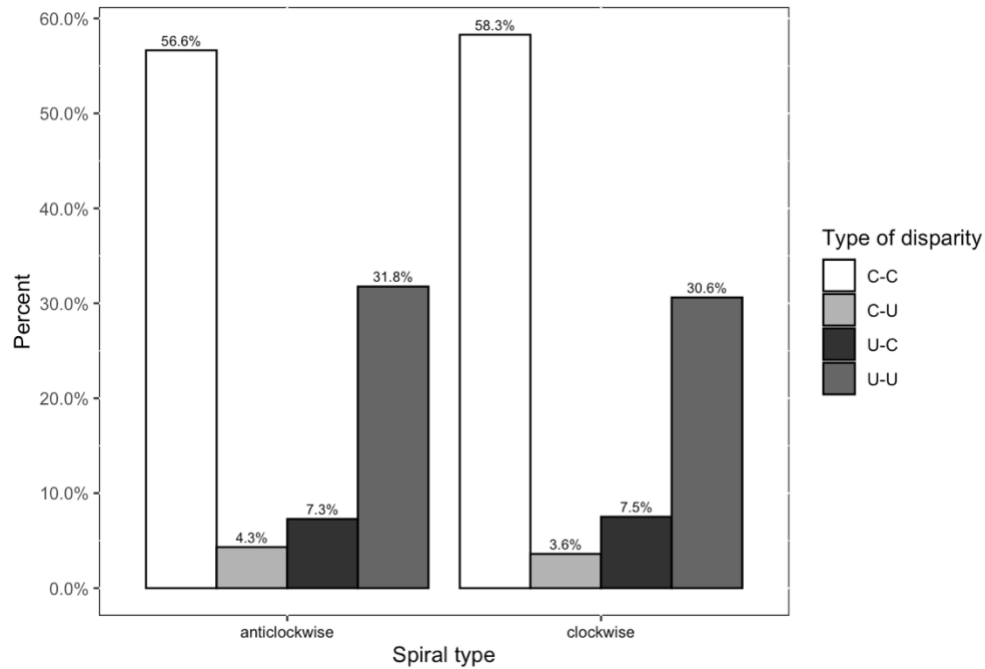


Figure 8.6 The distribution of disparity at the beginning and end of fixations in both spirals. C-C and U-U are the most frequent types of distribution in both spirals.

Figure 8.6 shows the distribution of the type of disparity at the beginning and end of fixations in both clockwise and anticlockwise spirals, with crossed (C) and uncrossed fixations (U); disparities at the beginning of fixation (crossed, uncrossed) and at the end of fixation (crossed, uncrossed) together as new variables to indicate both. Both spirals show very similar results, with the two dominant types being both the beginning and the end as crossed fixations (C-C) and both as uncrossed fixations (U-U). Figures 8.7 and 8.8 further show the horizontal and vertical distribution of disparity type in clockwise and anticlockwise spirals.

In the horizontal distribution, as shown in Figure 8.7, C-C fixations are the most dominant type at the left of the centre, whereas U-U is the most frequent distribution type at the right of the centre.

On the other hand, vertical distribution in Figure 8.8 shows a general concentration of C-C binocular fixation type at both upper and lower side of the centre in both spirals. Nonetheless, clockwise spirals show slightly greater distribution of C-C at the lower side of the centre whereas anticlockwise spirals show the similar trend above and below the centre.

The distribution of C-C and U-U fixation pairs can be further observed in Figure 8.9, with C-C concentrating at the right and lower side of the centre while U-U distributes more frequently at the left and lower side of the centre (note: the same pattern shown in two types of spirals so the heatmaps are combined to present together here).

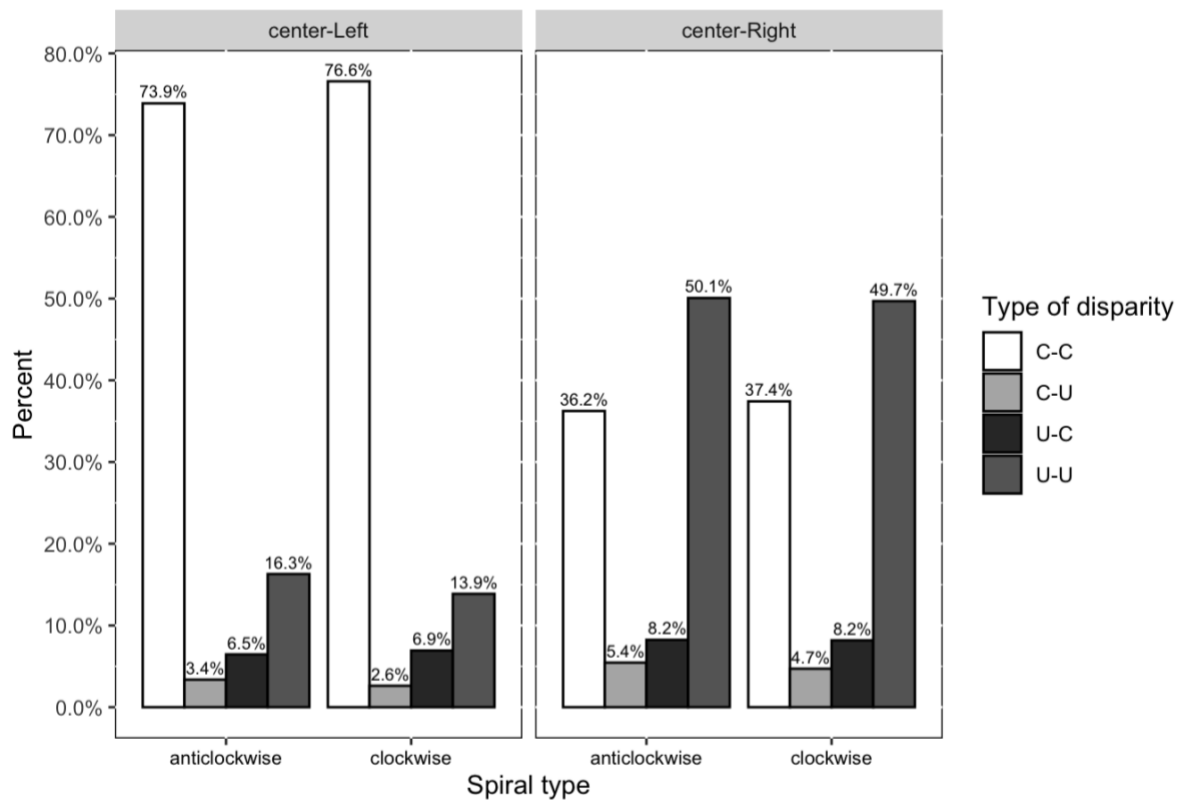


Figure 8.7 Horizontal distribution of disparity type in both spirals.
Most frequent type is C-C at the left of the centre and U-U at the right of the centre.

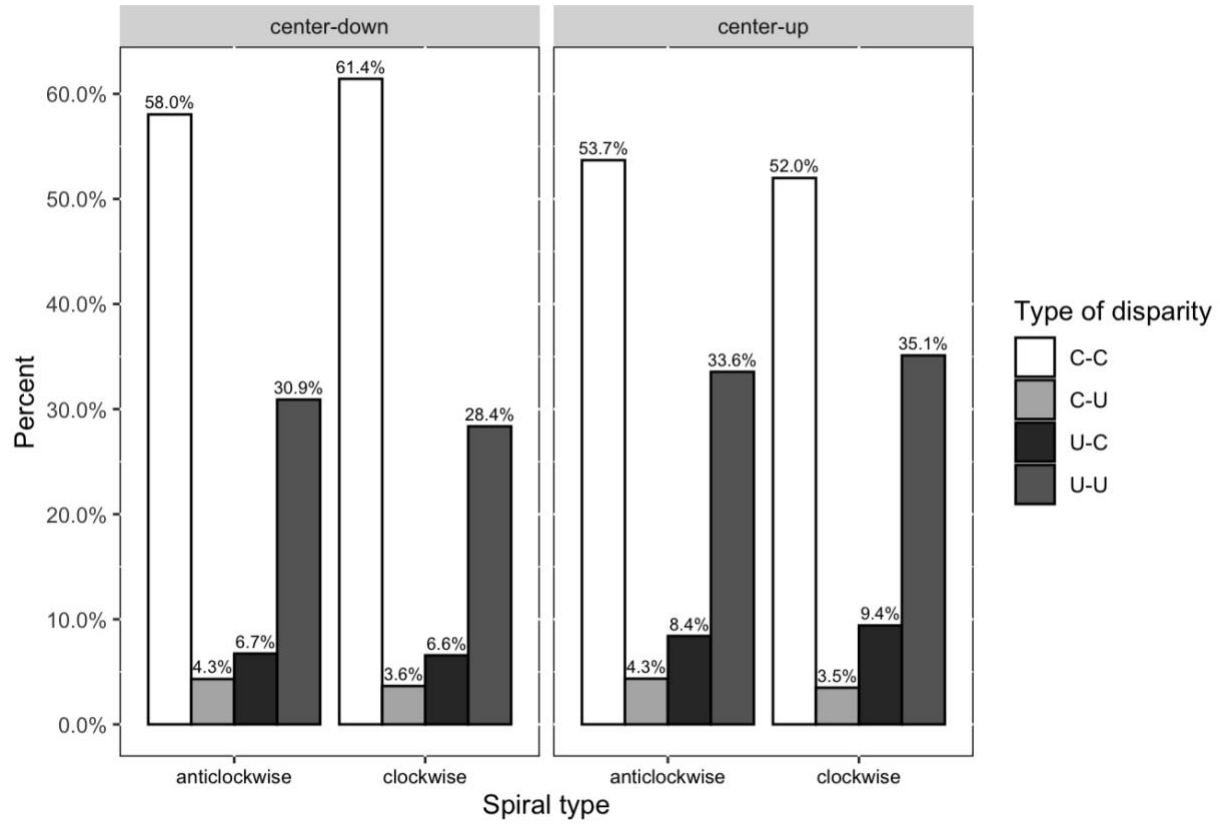


Figure 8.8 Vertical distribution of disparity type in both spirals. Greater concentration of C-C can be found at both upper and lower centre in both conditions.

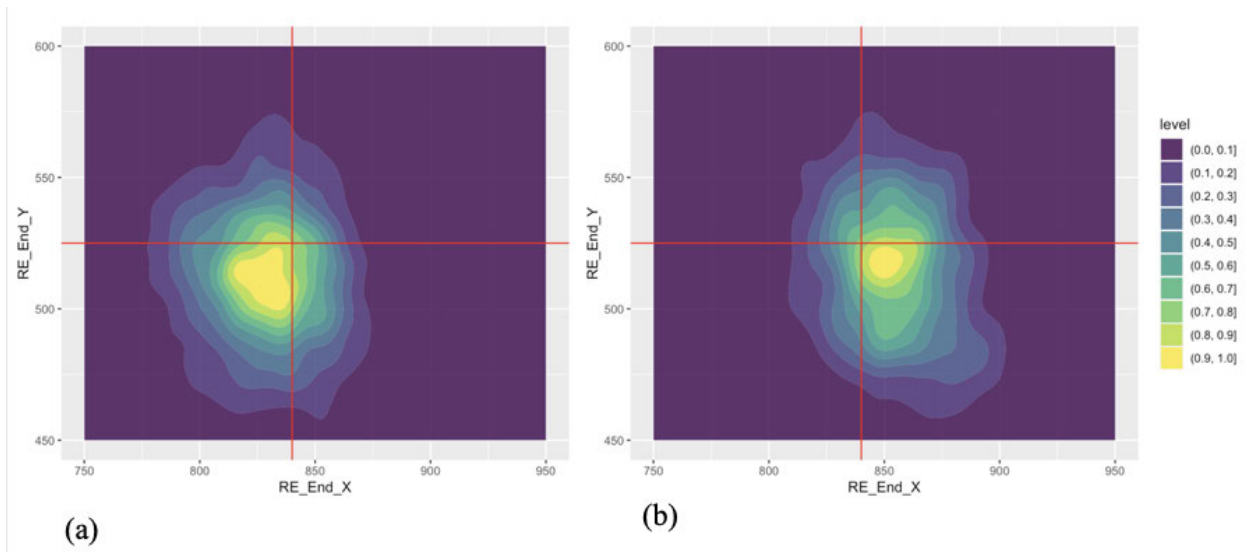


Figure 8.9 Spatial distribution of disparity type in both spirals in (a) crossed and (b) uncrossed fixation disparities. Data combined for clockwise and anticlockwise direction of rotation.

8.3.2 Modelling results

We used both Linear Mixed-Effects Regression Models (LMER) and General Linear Mixed-Effects Regression Models (GLMER) for quantitative analyses, carried out in R using the lme4 software package (Bates, Maechler, & Dai, 2008). Modelling results contain two parts, including binocular behaviours and the absolute travelling distance of the eyes. In the GLMER models, we used counts of fixation pairs as dependent variables in the models. We defined null models with participants as random factors. Predictor variables included the type of vergence during the fixation (convergence, divergence), the type of spirals (clockwise, anticlockwise), the horizontal position of the fixation (left of centre, right of centre), the vertical position of fixation (upper centre[centre-up], lower centre[centre-down]), and the type of disparity including C-C (i.e. crossed at both the beginning and end of fixation) and U-U (i.e. uncrossed at both the beginning and end of fixation). In the LMER models, we used the absolute movement of the eyes (i.e. absolute travelling distance on the horizontal axis of the end of fixation minus the beginning of the fixation in each eye) as dependent variables in the models. We defined null models with participants as random factors. Predictor variables included the horizontal position of the fixation (left of centre, right of centre), the type of spiral (clockwise, anticlockwise). All Model fit was assessed using the anova function to compare models.

8.3.2.1 Vergence type during the fixation in both spirals

8.3.2.1.1 General distribution of vergence type

	The number of fixations	
	no interaction (1)	Spiral type*vergence (2)
Anticlockwise	0.017 (0.508)	-0.027 (0.423)
Diverge	-0.148 (<0.001)	-0.199 (<0.001)

Anticlockwise:Diverge	0.099 (0.050)	
Constant	1.722 (<0.001)	1.744 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	0.3043	0.5516
Trial(4)	0.0002	0.0169
Observations	1,054	1,054
Log Likelihood	-3,685.673	-3,683.767
Akaike Inf. Crit.	7,381.347	7,379.534
Bayesian Inf. Crit.	7,406.149	7,409.296

Note: p value in parentheses.

Table 8.1 *The interaction of spiral type and disparity type in GLMER model 1*

	The number of fixations	
	no interaction (1)	spiral type*vergence (2)
Clockwise	-0.017 (0.508)	-0.072 (0.057)
Converge	0.148 (<0.001)	0.100 (<0.001)
Clockwise:Converge		0.099 (0.050)
Constant	1.591 (<0.001)	1.616 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	0.3043	0.5516
Trial(4)	0.0002	0.0169
Observations	1,054	1,054
Log Likelihood	-3,685.673	-3,683.767
Akaike Inf. Crit.	7,381.347	7,379.534
Bayesian Inf. Crit.	7,406.149	7,409.296

Note: p value in parentheses.

Table 8.2 *The interaction of spiral type and disparity type in GLMER model 2*

Results from GLMER models in Table 8.1 show that the counts of divergence fixation pairs is just significant, with more for the anticlockwise spirals. The model in Table 8.2 that changed the reference of the variables indicates a similar just significant result for the distribution of converging binocular fixations in clockwise spirals. The two models together are in accordance with the descriptive plot in Figure 8.3, with significantly more of the converging fixations in the clockwise spirals and diverging fixations in the anticlockwise spirals.

8.3.2.1.2 Horizontal distribution of vergence in clockwise and anticlockwise spirals

	The number of fixations	
	no interaction (1)	Vergence*horizontal position (2)
converge	0.329 (<0.001)	0.209 (<0.001)
center-left	0.097 (<0.001)	-0.034 (0.538)
converge:center-left		0.228 (0.001)
Constant	2.613 (<0.001)	2.679 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	0.4133	0.6429
Observations	149	149
Log Likelihood	-783.363	-778.525
Akaike Inf. Crit.	1,574.726	1,567.051
Bayesian Inf. Crit.	1,586.742	1,582.071

Note: p value in parentheses.

Table 8.3 *The horizontal distribution of vergence in clockwise spirals (GLMER)*

	The number of fixations	
	no interaction (1)	Vergence*horizontal position (2)
converge	0.199 (<0.001)	0.153 (0.003)
center-left	0.136 (<0.001)	0.091 (0.078)
converge:center-left		0.084 (0.232)
Constant	2.754 (<0.001)	2.778 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	0.4133	0.6429
Observations	151	151
Log Likelihood	-828.205	-827.495
Akaike Inf. Crit.	1,664.410	1,664.990
Bayesian Inf. Crit.	1,676.479	1,680.076

Note: p value in parentheses.

Table 8.4 *The horizontal distribution of vergence in anticlockwise spirals (GLMER)*

Table 8.3 and 8.4 show the horizontal distribution of vergence (i.e. convergence and divergence) in clockwise and anticlockwise spirals respectively. As shown in Table 8.3, converging fixations distribute significantly more at the left of the centre in the clockwise spiral, whereas a significant difference did not appear in the anticlockwise spirals, in accordance with

Figure 8.4. The models in both tables with no interaction also indicate a general concentration of binocular fixations at the left of the centre and dominance of convergence in both spirals, reflecting the results shown in Figure 8.3 and Figure 8.4 as well.

8.3.2.1.3 Vertical distribution of vergence in clockwise and anticlockwise spirals

	The number of fixations	
	no interaction	Disparity*vertical position
	(1)	(2)
converge	0.320 (<0.001)	0.363 (<0.001)
center-down	0.672 (<0.001)	0.709 (<0.001)
converge:center-down		-0.064 (0.407)
Constant	2.284 (<0.001)	2.258 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	0.3917	0.6258
Observations	148	148
Log Likelihood	-865.403	-865.060
Akaike Inf. Crit.	1,738.805	1,740.121
Bayesian Inf. Crit.	1,750.794	1,755.107

Note: p value in parentheses.

Table 8.5 The vertical distribution of vergence in clockwise spirals (GLMER)

	The number of fixations	
	no interaction	Disparity*vertical position
	(1)	(2)
converge	0.153 (<0.001)	0.225 (<0.001)
center-down	0.698 (<0.001)	0.756 (<0.001)
converge:center-down		-0.106 (0.157)
Constant	2.463 (<0.001)	2.423 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	0.3045	0.5518
Observations	147	147
Log Likelihood	-860.588	-859.594
Akaike Inf. Crit.	1,729.175	1,729.188
Bayesian Inf. Crit.	1,741.137	1,744.140

Note: p value in parentheses.

Table 8.6 The vertical distribution of vergence in anticlockwise spirals (GLMER)

Tables 8.5 and 8.6 show the vertical distribution of vergence in the clockwise and anticlockwise spirals respectively. Similar to the result shown in Figure 8.5, significantly more convergence data can be found in both clockwise and anticlockwise spirals, regardless of the vertical position. In addition, the models with no interaction also indicate a significantly greater distribution at the lower side of the centre and a dominance of convergence in both spirals, also in accordance with the general distribution shown in Figure 8.3 and Figure 8.5.

8.3.2.2 Horizontal & vertical distribution of disparity type in both spirals

	The number of fixations	
	no interaction (1)	Disparity*horizontal position (2)
C-C	0.353 (<0.001)	-0.595 (<0.001)
center-left	0.106 (<0.001)	-0.681 (<0.001)
center-down	0.639 (<0.001)	0.592 (<0.001)
C-C:center-left		1.401 (<0.001)
C-C:center-down		0.166 (0.053)
center-left:center-down		-0.554 (<0.001)
C-C:center-left:center-down		0.551 (<0.001)
Constant	1.684 (<0.001)	2.155 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	0.3279	0.5726
Spiral type(2)	0.0004	0.0212
Observations	465	465
Log Likelihood	-3,119.784	-2,660.806
Akaike Inf. Crit.	6,251.567	5,341.612
Bayesian Inf. Crit.	6,276.419	5,383.033

Note: p value in parentheses.

Table 8.7 The interaction of spatial distribution and disparity type in both spirals (GLMER)

	The number of fixations	
	no interaction (1)	Disparity*horizontal position (2)
U-U	-0.353 (<0.001)	-0.807 (<0.001)
center-right	-0.106 (<0.001)	-0.720 (<0.001)
center-down	0.639 (<0.001)	0.756 (<0.001)
U-U:center-right		1.401 (<0.001)
U-U:center-down		-0.717 (<0.001)
center-right:center-down		0.003 (0.971)
U-U:center-right:center-down		0.551 (<0.001)
Constant	2.143 (<0.001)	2.280 (<0.001)

Random effects		
	Variance	Std.Dev.
Participant(38)	0.3279	0.5726
Spiral type(2)	0.0004	0.0212
Observations	465	465
Log Likelihood	-3,119.784	-2,660.806
Akaike Inf. Crit.	6,251.567	5,341.612
Bayesian Inf. Crit.	6,276.419	5,383.033

Note: p value in parentheses.

Table 8.8 *The interaction of spatial distribution and disparity type in both spirals (GLMER)*

Tables 8.7 and 8.8 shows the interaction of spatial position with the type of disparity; they support the previous descriptive presentations statistically. Table 8.7 shows the statistical significance of the crossed fixations distribution at the left and lower centre more than expected, whereas Table 8.8 supports the similar finding in uncrossed fixations, revealing a significant distribution at the right and the lower centre. All the results are in accord with the previous descriptive results in Figure 8.9.

8.3.2.3 Travelling distance and the division of labour in the two eyes

Tables 8.9 and 8.10 show the interaction between the type of disparity and the horizontal position of the binocular fixation in terms of the absolute movement of the right eye and the left eye respectively. The absolute horizontal movement of the right eye in Table 8.9 shows slightly longer significant movement at the right of centre for the right eye, regardless of the type of spiral. Similar results are found in the absolute horizontal movement of the left eye, as shown in Table 8.10, that the left eye also travels in a significantly longer movement at the right of centre, not influenced by the type of spiral. Though the findings are different from our prediction about the division of labour where the left eye might tend to travel more at the left of the centre and the right

eye would travel longer at the right of the centre, we suggest the result may be related to the fact of more uncrossed fixations and divergence at the right of the centre.

	Movement during fixation	
	No interaction (1)	Spiral type*horizontal position (2)
contracting	-0.131 (0.725)	-0.345 (0.498)
centre-right	1.395 (0.001)	1.171 (0.032)
contracting:centre-right		0.462 (0.537)
Constant	11.730 (<0.001)	11.831 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	12.6	3.55
Trial(4)	0.305	0.552
Observations	6,371	6,371
Log Likelihood	-26,229.640	-26,228.830
Akaike Inf. Crit.	52,469.290	52,469.650
Bayesian Inf. Crit.	52,503.090	52,510.210

Note: p value in parentheses.

Table 8.9 The horizontal movement of the right eye during the fixation in both spirals (LMER)

	Movement during fixation	
	No interaction (1)	Spiral type*horizontal position (2)
contracting	-0.285 (0.507)	0.462 (0.069)
center-right	1.219 (0.010)	2.002 (0.002)
contracting:center-right		-1.611 (0.062)
Constant	12.859 (<0.001)	12.505 (<0.001)
Random effects		
	Variance	Std.Dev.
Participant(38)	15.25	3.905
Observations	6,371	6,371
Log Likelihood	-27,141.550	-27,139.030
Akaike Inf. Crit.	54,293.100	54,290.070
Bayesian Inf. Crit.	54,326.900	54,330.620

Note: p value in parentheses.

Table 8.10 The horizontal movement of the left eye during the fixation in both spirals (LMER)

8.4 Discussion

Rotating spirals are widely used in the psychology of after-effects. They are referred to as ‘expanding’ or ‘contracting’ (referring to their perceived approach or retreat) and as objectively rotating clockwise or anticlockwise. They may also differ in the direction of the swirl in the static stimulus; in Fig. 8.1 and 8.2 the white swirls spiral in towards the centre in a clockwise and anticlockwise manner. Critically, there is a different perception depending on whether the spiral stimulus is rotated clockwise or anticlockwise.

What is the nature of this perception? Just given the static disc, we might initially predict that any perceived motion would resemble the round front of a locomotive either speeding towards us or retreating away from us; we could then generate hypotheses regarding the eyes converging more and more to stay focused on the approaching train or diverging more and more to stay focused on the departing train. However, what happens when the disc is rotating is that the perception of the stimulus is actually one of looking down a well shaft and feeling one is falling down the shaft (anticlockwise motion) or being pulled up the same shaft (clockwise motion). (If anything, the anticlockwise one is more ‘natural’, in that the viewer moving forward—however fast—occurs more frequently in the real world.) Given these perceptions, it is not so easy to make predictions about whether the eyes should be converging or diverging. Is the viewer trying to focus on the departing bottom of the well? Or the nearby sides of the well flashing past? All we can say is that there is a different, consistent perceptual illusion in each case. Any aftereffect is naturally in the opposite direction.

In our experiment, we found some similarities in perceiving the two different rotating spirals, including a general higher concentration of convergence and C-C binocular feature as well as a spatial focus of the binocular fixations at the left of the centre and lower side of the centre, even

with the subjective attempt to fixate at the centre according to participants' instructions. The difference itself relates to more specific features and the sensitivity of the visual system to processing requirements of orientation in illusory motions, with relatively general higher divergence in viewing the anticlockwise spiral and more convergence in clockwise spiral. Also, the clockwise rotation shows greater difference of distribution of C-C fixations at the upper and lower centre compared to the anticlockwise, even though both produce generally more C-C data. This appeals to our first prediction partially.

Fig. 8.3 and Fig. 8.4 show almost identical effects for the two types of spiral: more fixation left of centre than right of centre and more fixations below centre than above centre. Also no outstanding differences are found between the two conditions in terms of some particular effect, with vergence movement and spatial distribution in our results. Then we could think about what dimensions are *similar* between the two conditions, Perhaps, our viewers naturally prefer to fixate the top-left of any screen, as in beginning reading a page of text? This suggestion is not particularly convincing as we also see a strong preference for fixating the lower part of the stimuli (Fig. 8.4), just as our third prediction. We also know that for scenes there is a strong tendency to fixate the *middle* of the scene (Tatler, 2007); some aspect of this behaviour might be culturally acquired, in that photographers naturally position the interesting element in the middle of the picture. In our experiment, participants show a *spatial preference* for visual attention regardless of the instruction to fixate the centre.

Left of centre fixations project more of the stimulus to the left hemisphere (LH) and right of centre fixations project more of the stimulus to the right hemisphere (RH). Participants preferred to send the larger part of both stimuli to the LH. In addition, fixations on the lower part of the stimulus mean that the larger part of the stimulus is being projected to the ventral visual pathway,

whereas fixations above the centre of the stimulus project the larger part of the stimulus to the dorsal visual pathway. Our participants were strongly preferring to project the larger part of the stimulus to the ventral pathway, in both spirals.

Perhaps there are hemispheric preferences that caused the participants to favour the lower left part of the stimulus, and thus projection to the LH and the ventral pathway? The LH seems to specialise in processing horizontal aspects of stimuli (Pettigrew, 2001), but there seems to be no reason to believe that the spiral is more of a horizontal than a vertical phenomenon. If we expected the viewers to respond to the aversiveness of the stimulus, we might have expected to see them sending most of the stimulus to the RH, which deals with novelty. We saw the opposite, suggesting the aversiveness of the stimulus was not a consideration.

The early characterisation of the dorsal-ventral distinction (Goodale & Milner, 1992) as visually-guided actions versus perceptual identification has evolved over the years. Clark (2009) could say of the dual visual systems model that it was “still revealing after all these years”.

In the last two decades and before, the dorsal pathway has been claimed to be concerned with spatial attention, spatial scaling, and magnitude estimation (e.g. Buetti & Walsh, 2009; Fias, Lammertyn, Reynvoet, Dupont & Orban, 2003; Parton, Malhotra & Husain, 2004). Speculatively, it may be that the brain's priority is to recognise objects in the field of view. It may also be the case that the viewer is trying to avoid projecting the stimulus to the dorsal pathway for the very reason that the stimulus does not ‘make sense’.

Schenk and McIntosh (2010) review the limits of the distinction between the two streams, allowing only that Milner and Goodale's perception-action model “captures some broad patterns of functional localization” but that the two streams are only relatively specialized, with extensive

inter-stream interactions. The technologies in all areas of Cognitive Neuroscience have advanced enormously since the early 1990s (McIntosh & Schenk, 2009).

The original model has inspired a large amount of research over the decades, most of it making clear that there is sophisticated interaction between the two streams, as in controlling skilled grasp (Van Polanen & Davare, 2015), the role of colour (Garofalo & Riggio, 2022), monocular versus binocular depth cues (Niechwiej-Szwedo, Cao & Barnett-Cowan, 2022), the effect of visual illusion on grasping (Kopiske, Bruno, Hesse, Schenk & Franz, 2016). In contrast, there are demonstrations of the autonomy of processing in the two streams, as in van Polanen's (2021) demonstration that size perception is not altered by grasp aperture corrections in reach-to-grasp movements.

The linear, hierarchical nature of the perception-action model has been criticised from the perspective of other frameworks, such as network modelling (de Haan & Cowey, 2011), deep learning involving both streams and a single visual input (Wen et al., 2018), the linkage with perceptual awareness (Hesselmann & Malach, 2011), the role of consciousness (Kozuch, 2022; Shepherd, 2015), and the study of visual impairment (Rossetti, Pisella, & McIntosh, 2017).

The relationship between the two pathways is still being revealed 13 years after Clark's statement. This progress does not detract from the very clear data we report in viewing Plateau's spiral, but it does make its interpretation even more intriguing and important for further study.

In addition, we might note that Neri, Bridge and Heeger (2004) have shown the ventral stream to be responsive to both absolute and relative disparity, whereas the dorsal stream specialises in absolute disparity. The task did not require reaching to the stimulus, which would have involved the dorsal stream more. Sending the larger part of the stimulus to the ventral stream

may also reflect this fact. Further research is required to understand the similarities in response to the two stimuli.

Figure 8.5 shows relatively similar responding to the two conditions, with convergence predominating over divergence, in general. Anticlockwise condition shows slightly greater divergence, but we can note here that convergence is typically seen within fixations on most stimuli. It is generally taken to indicate that the two eyes are moving towards a conjugate fixation on the same point, following the different profiles of acceleration of the two eyes during the saccade. Although we see the same preference for convergence over divergence in the two conditions, the difference is more marked in the clockwise condition when it comes to horizontal distribution in Figure 8.6. Clockwise spirals seem to elicit a greater concentration of convergent fixations at the left of the centre, which might suggest greater LH processing and relatively higher sensitivity of visual system toward the clockwise condition.

Similar interaction between fixation location and the cross-uncrossed distinction in both spirals can be found in Figures 8.9 and 8.10 as well. The LH prefers the crossed-crossed category. The RH prefers the uncrossed-uncrossed category, which is consistent with the results of more divergent eye movements projected to RH. Why should LH prefer crossed-crossed? The data from our neurotypical participants may be interpreted as complementary hemispheric processing in which the LH compensates for one type of directional fatigue and the RH compensates for its opposite. The mechanics of the eyes are such that they can either converge or diverge. Dividing the compensation at the level of the hemispheres (and dependent on where the viewer is looking) makes sense, in that each hemisphere's processing is relatively insulated from the other's. They jointly managed to compensate for fatigue.

Why should the RH prefer uncrossed-uncrossed? The crossed-crossed fixations place the horopter between the stimulus and the viewer. The stimulus is ‘sent’ to more distant space. The uncrossed-uncrossed fixations ‘bring’ the stimulus towards the viewer, placing it in peripersonal space. Our findings about the division of labour are also in favour of the longer and greater travel distance of both the left and the right eye, at the right of the centre, suggesting more work to be done in the right visual field in RH processing, though differ from our original second prediction. Halligan and Marshall (1991) describe a patient with a RH lesion and contralateral left visual neglect for peripersonal space but not for far space. This patient constituted the first evidence for dissociable processing of near and far space.

Thus, the RH seems to be responsible for resolving aspects of depth perception, for integrating disparate processes, for temporal flow and for perception of wholes (Gestalts). The strongest effect we have reported is the preference for uncrossed fixation disparities being directed to the RH. These effectively bring the challenging stimulus closer to the viewer (i.e., into peripersonal space) and may be interpreted as the viewer using the mechanics of eye movements to send this challenging stimulus to the RH for processing in one way (i.e., close-up) and to the LH for processing in another way (i.e. farther away).

The experiment with Plateau’s Spiral has shown dramatic effects on vergence behaviours. Fixation behaviours are used to exploit differing processing specialisms in the two hemispheres and in the dorsal and ventral pathways. These specialisms involve the differences between absolute and relative disparity and between flow and stasis, flatness, and depth. Once again, further research could turn towards AR technology to isolate the stimulus to particular eyes as well as to particular vertical or horizontal hemifields.

Chapter 9

Conclusion

In this thesis, we have discussed binocular strategies in both reading and non-reading tasks, from oculomotor behaviours and their implications to higher cognition.

In **chapter 1**, we have introduced the relevant literature and existing studies about visual perception in a wide range of perspectives, from general visual information processing to the function of binocularity. We discussed cross-linguistic reading behaviours with specific orthographic characteristics. We also reviewed task-specific research findings in non-reading tasks, with visual system performance and interaction with higher visual cognitive processing to understand how they could inspire the research we conducted in this thesis. Finally, we looked at the theories and findings about hemispheric processing and oculomotor prevalence, as the principles behind the collaborative behaviours of the two eyes in response to all these reading and non-reading visual tasks.

In **chapter 2**, we included the methodology of each chapter with different experimental settings as well as participants information.

In **chapter 3**, we investigated small temporal non-alignments between the two eyes' fixations in the reading of two very different orthographies, English and Chinese. We analysed nine patterns of temporal disjugacy, which is the small-scale temporary unyoking of the two eyes' fixations in time. We have found that the distribution of small asynchronies of binocular fixation accord with ocular prevalence. Our results show that:

(1) The left eye will tend to begin fixating earlier and stay fixating longer in the left visual field, and the right eye will be similarly prioritized in the right visual field, thereby facilitating the appropriate switching of ocular prevalence.

(2) A very similar pattern of binocular temporal asynchronies will be found even across the two very different orthographies of English and Chinese.

We argue that such asynchronies are predictive of ocular prevalence, in which input to the left eye is prioritized in conscious perception of a fused visual stimulus for targets in the left visual field and right-eye input is prioritized for targets in the right visual field. Ocular prevalence optimizes perception by (a) allowing the optimal interaction of monocular processing, respecting the differences in distortion and range for the images in the two eyes and their particularities, and (b) respecting the contralateral advantage. Asynchronies in which one eye begins the fixation earlier and/or ends it later occur most frequently in the hemifield corresponding to that eye.

Having one eye's fixation begin even slightly earlier may elicit prevalence for that input in higher perception and cognition. Having one eye's fixation end even slightly later may also be a way of eliciting a switch in prevalence or of respecting the existing prevalence. The distribution of asynchronies is very similar across the two very different orthographies of Chinese and English, suggesting it may apply across all left- to-right orthographies (LTROs).

A picture emerges in which the physical constraints on binocular eye movements are intimately involved with the higher-level conscious processing of the fused image. Reading benefits from ocular prevalence, such that the eye that is closest and squarest-on to the text has priority in the conscious fused percept of the text. We conclude that small binocular timing asynchronies contribute to ocular prevalence moving fluidly between the two eyes in skilled reading.

In **chapter 4**, we further investigate the temporal asynchronies reported in chapter 3 in the reading of right-to-left orthographies (RTLOs), Arabic and Hebrew. Cross-linguistic research on binocular coordination in reading has mainly focused on LTROs. However, there are important asymmetries in the visual pathways and cortical areas responsible for reading, so how does ocular prevalence play out in reading the RTLOs Arabic and Hebrew? We found that:

(1) Ocular prevalence: Arabic and Hebrew reading behaviours matched our predictions concerning ocular prevalence. Overall, the pattern of temporal asynchronies in the RTLOs closely resembled those of the previously reported LTROs: the RE's input tends to be prioritized on the right side of the screen and the LE's on the left side.

This is because ocular prevalence will favour the eye that is closest and most directly square-on to the text on the screen. This analysis extends the study of the reading of the LTROs English and Chinese in chapter 3. In RTLOs, as in LTROs, the LE will tend to begin fixating earlier and stay fixating longer in the LVF, and the RE will be similarly prioritized in the RVF, thereby facilitating the appropriate switching of ocular prevalence.

(2) Reading direction and symmetry: There is an overall quantitative *symmetry* of the data for the two directions of reading. The pattern of binocular temporal asynchronies in RTLOs exactly mirror the pattern in the LTROs English and Chinese.

This is due to symmetrical horizontal movement of the eyes alone that is responsible for the pattern of behaviour. This symmetry is a critical confirmation of our claim that the observed asynchronies in LTROs resulted from anatomical constraints interacting with the direction of reading. Any departure from exact symmetry will implicate the asymmetries in projection represented by RE ocular dominance and/or by any specialization for reading behaviours in each of the hemispheres.

(3) Hemispheric specialization and asymmetry: two unexpected departures from symmetry can be found T1 and T2 (i.e., fixation ends that favour the LE and RE respectively) in RTLOs. We suggest that the specific patterns from RTLOs is associated with the asymmetry between lexical processing in the two hemispheres and the direction of reading.

We discussed how the evident hemispheric asymmetry in parafoveal lookahead may be reflected in the nature of right-to-left orthographic conventions. There are pros and cons regarding reading direction. We might expect the farthest lookahead going directly to the RH to elicit orthographic conventions that match the known processing propensities of the RH. A RTLO may exploit the RH's capacity for coarse coding, for taking *context* of all kinds into account. The converse arguments apply with respect to LTROs and the strengths of the LH. Word recognition takes advantage of the full orthographic specification of words. The phonological form of words in a language may favour a direction of writing, also, with a direction of reading in place, we can expect the exigencies of foveal splitting and hemispheric differences to assert themselves over cultural time.

We conclude that a language tends to get the orthographic conventions that the reading direction and the hemispheres deserve.

In **chapter 5**, we turned to explore how the visual system reacts and adapts to the continuous text-background contrast in a reading-like task. In a number-reading task, the background becomes more and more faded while the text stimuli stay bright and white, with decreasing contrast and increasing reading difficulty. Little has previously been investigated to understand the influence of contrast variation on the specifics of binocular behaviour. We studied binocular adaptative behaviours in terms of fixation disparity. The results show:

(1) A systematic adaptation of binocular vision in response to the contrast change, with an overall crossed tendency of binocular fixations (right eye's fixation to the left of the left eye's fixation), both qualitatively and quantitatively. The number of crossed fixations increases as the level of contrast decreases.

Crossed fixations are the norm for general levels of illumination close to normal room lighting. Such fixations benefit the reader by overlaying the two privileged contralateral projections in the middle of the perceptual window for reading. We suggest that the crossed fixation is optimal for these conditions because the centre of the foveal window consists of the overlap of these two best retina-to-cortex projections—the contralateral projection from each eye: RE to LH and LE to RH. These behaviours indicate binocular contrast adaptation and a potential processing advantage for crossed fixations.

(2) Binocular disparity also adapts to variation in text-background contrast. We found increasing numbers of crossed fixations together with decreasing disparities as the contrast became lower and reading difficulty increased.

As discussed above, an overall crossed tendency facilitates visual processing quality by exploiting the central part of the perceptual window. In addition, binocular fusion for ambiguous input such as the lower contrast parts of the stimulus will be improved by a smaller fixation disparity, meaning that there is greater overlap between the foveal input from the two eyes. We suggest having a relatively large fixation disparity in the relatively readable contrast conditions is optimal because a wider extent of the line is in view and is afforded the best projection conditions—that existing between the two fixation points.

As the reading difficulty increases and the contrast makes it relatively harder to recognise numbers, increasing crossed fixations and smaller disparities seems to indicate a 'zooming in' to

a particularly very difficult-to-read section of the line. It suggests that there is the capacity to project the critical region between the two fixation points onto a larger area of cortex, so as to increase the chances of discriminating the numbers from the background.

Overall, the binocular contrast adaptation through very peripheral muscle-driven movements of the eyes implies an effect in cortical processing that contributes to cognition and potential synchronised correlation with the underlying neural circuits.

These visual adaptative behaviours all indicates a systematic and harmonious visual activity showing the flexibility of the visual system via different modes of operation, from the basic neural units to peripheral binocular movement and all the way to the higher cognitive processing, in response to the contrast change in the stimuli.

In **Chapter 6**, we further investigated how the visual system reacts and adapts to the level of faintness, in a number reading task. In the reading-like task, the text becomes more and more blurred while the background stays bright and white, with increasing blurriness and reading difficulty. Jaschinski-Kruza (1994) report a shift to an exophoric (i.e., uncrossed) fixation disparities elicited by increased blurriness of text stimuli. Jainta et al. (2010) also report the adjusted vergence of binocular performance to read blurry stimuli. Our results are consistent with previous findings:

(1) We found a considerable increasing distribution of uncrossed fixation pairs as the level of blurriness of the text stimuli increases and reading difficulty increases, though with an overall crossed tendency of binocular fixations.

These overall effects suggest a general trend of the reading of blurry stimuli appealing to uncrossed-uncrossed (start and end of fixation) binocular adaptative behaviours. These uncrossed

patterns facilitate binocular fusion through creating stereo input with better processing at the extremes of the perceptual window for higher quality information, through the contralateral advantage. The adaptive binocular performance indicates strategic behaviours of the visual system to optimise visual processing with blurred stimuli.

(2) These binocular behaviours are modulated based on the level of faintness of the texts and reveal an adaptive performance. The two eyes coordinate to accommodate and adjust for better visual quality and performance in different conditions such as blurred text.

In **chapter 7**, we investigated how the visual system reacts and responds to a visual illusion created by depth information as a cue for judgement of perceived size. We replicated Murray et al.'s (2006) experiment with far and near spheres and investigated the possible change of eye-movement behaviours to adapt to far and near objects under natural viewing conditions. We used two spheres of the same size, perceived differently due to their background, under two viewing conditions (i.e., each sphere at a time; two spheres together) and analysed participants' vergence behaviours.

We manipulated the task in ways that might affect the experience of the illusion and that also might elicit different eye-movement behaviours, namely by requiring subjects (a) to fixate a single visible sphere in either location and (b) by requiring subjects to move back and forwards between two coexisting spheres in the two locations.

The general question we explored here is: are there any eye-movement behaviours that differ between viewing the 'near' and 'far' spheres and can we interpret them in terms of this preparation for active engagement with the objects of the world?

In our results, we found that: 1) There are opposite results from two different viewing tasks, as well as differences in eye-movement behaviours involving vergence movements at the ‘near’ and ‘far’ sphere in both viewing tasks. Murray et al. (2006) assumed, first, closely conjoint fixations by the two eyes and, second, robustness across viewing tasks. We have shown that these assumptions are simplifications. The result overall suggests an alternative interpretation to Murray et al.’s (2006) (and one that they dismissed at the time without directly relevant data): that the apparent VI correlate of the size illusion may be partially attributable to larger binocular fixation disparities in some tasks.

2) The results from Task 1 show convergence at the front sphere and divergence at the back sphere, which suggests that in the illusion the same pattern of convergence and divergence will obtain at some point in fixation as when looking at real objects, hence indicating the responses by the two eyes to the depth cues. There is more divergence, or disparity, at the ‘far’ sphere which might suggest that the projection of the fixated sphere by the two eyes is occupying more of V1.

3) There are more convergence fixations in Task 2 as the ‘far’ sphere is being fixated in the same task. This eye-movement behaviour is coherent with looking at things that differ in depth but without accommodating the eyes to focus on different depths. This eye-movement behaviour involves vergence movements in which the two eyes converge so as to place the intersection of the two lines of sight (i.e., the horopter) between the illusorily farther away sphere and the viewer.

The results are in accord with Cornell et al.’s (2003) findings concerning binocular eye movements under near and far conditions, with under-convergence from near fixations and over-convergence for far fixations. It further implies the illusion reaches into the higher cortical regions of visual processing not just to the primary visual cortex, and all the way out to the very peripheral processing responsible for vergence.

Finally, in **Chapter 8**, we investigate binocular adaptative processing of the visual illusion elicited by viewing a challenging visual stimulus, Plateau's Spiral. Previous research has found visual sensitivity and neural adaptation in response to the processing of this rotational illusion. The main question we have explored is: how would the two eyes respond to stimuli that produce a motion-based illusion of depth, given that such stimuli produce not just an aftereffect but different perceptions *during* the stimulus? Our experiment included the two directions of motion in the experiment, clockwise and anticlockwise.

We found that: (1) It shows general similarities in processing the two types of spirals. Unlike our prediction, the result shows only slightly different perceptual effects produced in terms of vergence movement in viewing spirals with different directions of rotation.

(2) However, there was a remarkable difference in the binocular strategies in processing under different spatial positions.

- a) In vertical processing, participants produced a great concentration in the lower centre. This may be because participants viewing the disturbing spiral illusion will seek to minimize their discomfort by tending to fixate below the centre of the spiral, which will project the key part of the stimulus to the ventral visual pathway as opposed to the dorsal visual pathway. The ventral stream is more concerned with matching the visual stimulus against stored templates and creates less disturbance, compared to the dorsal pathway, which is concerned with spatial attention, spatial scaling, and magnitude estimation.
- b) In horizontal processing, a clear difference was found with predominantly crossed fixations at the left and the uncrossed at the right of the centre. The results show that the direction of fixation disparity changed according to whether fixation directed the

largest part of the stimulus to the left or right hemisphere. The oculomotor system might just produce directions of retinal disparities matching the strengths and preferences of the hemispheric visual processing domains.

It all indicated hemispheric specialisation and projection during viewing an illusional stimulus and corresponding binocular strategies for visual processing. Perception can be manipulated by hemisphere-based higher cognition controlling the oculomotor musculature, allowing the hemispheres to generate their own most appropriate input, when viewing a visually challenging stimulus, Plateau's Spiral.

Appendix

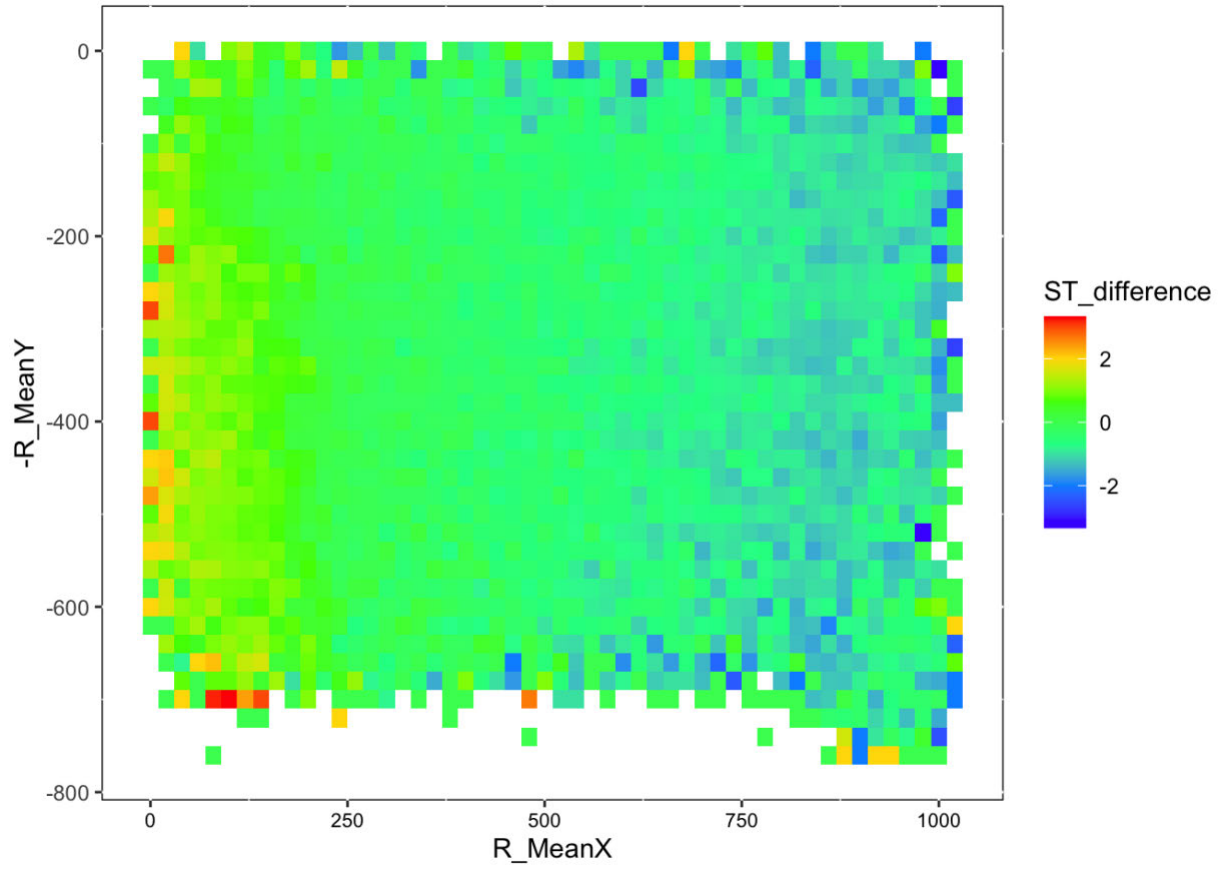


Figure A.1 Spatial distribution of starting offsets and how it varies across the page.

	StartTime offsets (1)	EndTime offsets (2)
L_Fix_duration	0.385 (<0.001)	-0.615 (<0.001)
R_Fix_duration	-0.384 (<0.001)	0.616 (<0.001)
R_Previous_saccade	-0.0001 (0.865)	-0.0001 (0.865)
L_Previous_saccade	-0.001 (0.031)	-0.001 (0.031)
Start_disparity	0.054 (<0.001)	0.054 (<0.001)
End_disparity	0.126 (<0.001)	0.126 (<0.001)
Mean_disparity	-0.181 (<0.001)	-0.181 (<0.001)
Constant	-0.501 (<0.001)	-0.501 (<0.001)
Observations	311,452	311,452
R ²	0.450	0.665
Adjusted R ²	0.450	0.665
Residual Std. Error (df = 311444)	4.169	4.169
F Statistic (df = 7; 311444)	36,347.120 (p = 0.000)	88,263.260 (p = 0.000)

Note: p value in parentheses.

Table A.1 Multivariate polynomial regression analysis of *StartTime* and *EndTime* offsets.

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