THE INFLUENCE OF DIRECTIONALITY BIAS ON VISION FOR ACTION AND VISION FOR PERCEPTION

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ABSTRACT

I investigated the sensitivity of the visual system to directionality bias by manipulating the likely direction of a horizontally moving target. I went on to examine the generalizability of directionality bias on the visual system during perceptual tasks, for which an action was not required. Forty-eight participants completed a visuomotor task and two line bisections tests, one prior to the visuomotor task and one after it. The visuomotor task consisted of a two-dimensional rectangular target appearing in the middle of a monitor and horizontally translating towards the right or the left. Participants were randomly assigned to one of two groups, a rightward bias group (75% R – 25% L) or a leftward bias group (25% R – 75% L). Results revealed that participants did not make anticipatory fixations in the direction in which the target would move prior to its movement. However, I did observe that following the movement of the target, participants became better at following the target closer to its center, as they completed more trials. Nevertheless, for both, fixations before and after target movement onset, there was no significant difference between the rightward and leftward bias groups. Finally, contrary to my hypothesis, the line bisection task revealed a rightward bias, which was not affected by the directional bias introduced during the visuomotor task. These results suggest that a 75% – 25% bias ratio is not sufficient to cause the visuomotor system to produce anticipatory fixation behaviour. Moreover, results of the line bisection task did not show pseudoneglect, but instead a rightward bias, providing support for the interhemispheric competition theory of visual attention.

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CHAPTER I

GENERAL INTRODUCTION

Grabbing a cup of coffee or picking up the phone off a desk to answer a text message are just a few examples of movements that people perform daily as they interact with their environment. People typically perform reaching and grasping actions without considering the complex underlying neural processes that control these behaviours. Although they seem easy to perform, goal-directed actions require the brain to solve the difficult spatial problem of coordinating visual information related to the object, the environment, and the hand, with tactile and proprioceptive feedback from the body, to produce a fluid motor action (Goodale, 2011).

For a person to complete a simple goal-directed action such as grabbing a cup of coffee off a desk, two steps must be completed. First, the person must search for the cup of coffee in the array of distractions present on the desk. Second, the brain must compute the fixation/landing position of the hand upon that cup of coffee (Vishwanath & Kowler, 2004). When searching for, or reaching to grasp, an object, people can exploit the target location probabilities (Geng & Behrmann, 2005; Kowler, 2011). For example, the person who wishes to grab the cup of coffee off the desk will intuitively know that the cup of coffee is more likely to be next to the stack of papers on the desk than on top of the monitor. Exploiting those probabilities allows people to fixate on objects before manipulating them by a few moments, increasing the chances of successfully executing the behaviour (Mennie et al., 2007).

Goal-directed actions performed on moving objects are more complicated than ones performed to manipulate stationary objects. Grasping a moving object also requires the brain to use visual information to make complex calculations regarding the object's position and velocity, since the hand must be aimed towards the location where the object will be at the time of contact

(Todd, 1981). For instance, when attempting to catch the ball, a soccer goalie must anticipate the direction the ball will be shot to jump to that side and catch the ball before it crosses the goal line. If the goalie fails to correctly anticipate the ball's direction, the opposing team will likely score a goal. Research shows that humans are quite skilled at obtaining the needed visual information to complete these kinds of complex goal-directed action.

Previous research has shown that when attempting to grasp a horizontally moving object, participants anticipate the object's horizontal movement by fixating ahead of the object's edge in the direction of its movement (Daye et al., 2014). Similar results have been found by studies that utilized two-dimensional targets (Bulloch et al., 2014). Once a person's reaching movement is initiated, they begin fixating towards the top edge of the object, which corresponds to the index finger's final contact point (Desanghere, & Marotta, 2010, 2011; Króliczak et al., 2007). When attempting to grasp an object, fixation positions within the object's boundaries differ depending on its movement status (Johansson et al., 2001). Hence, it is possible that the brain uses more information than the velocity and position of an object to guide goal-directed behaviour towards moving objects. It is not yet known if the visuomotor system is able to utilize directionality bias of a moving target from its movement history. Directionality bias refers to the bias created as a result of a target moving towards one direction significantly more often than other directions. Moreover, if the visuomotor system can detect and utilize directionality bias when executing goal-directed behaviour, it is not well understood whether that bias would influence perception of the target object.

Dual-Stream theory

It has long been proposed that visual information utilized for action is processed in a different neural pathway than visual information utilized for perception. Schneider (1969) was the first to suggest that the visual system consists of two parts, a part for identification and a part for localization. Mishkin and colleagues (1983) extended this research by distinguishing two extrastriate visual pathways: a dorsal stream projecting from the primary visual cortex to the posterior parietal cortex, and a ventral pathway projecting from the primary visual cortex to the inferotemporal cortex. Mishkin and colleagues theorized that the dorsal stream processes information regarding the spatial properties of an object and named it the “where” pathway. Moreover, they theorized that the ventral stream processes information for object identification and named it the “what” pathway (Mishkin et., 1983).

Goodale and Milner came up with an alternative theory suggesting that what differentiates the dorsal and ventral streams is not the kind of information they process, but rather, how they use that information (Milner and Goodale, 2006). Support for this viewpoint largely came from case studies. Patient D.F. suffered from a selective lesion to her ventral stream causing her to suffer from visual form agnosia, a disorder characterized by the inability to recognize objects, copy or draw them, or recognize them when presented in the form of a drawing (Goodale et al., 1991; Milner and Goodale, 2006). However, Patient D.F.’s Dorsal stream was completely intact. When patient D.F. was presented with three-dimensional objects, she failed to recognize these objects. However, she was able to reach and interact with them successfully, meaning that she was able to transport her arm to the correct location and preshape her hand and fingers in relation to the object’s shape and size accurately to ensure successful grasp of the object (Goodale et al., 1991).

Another remarkable case study was conducted with Patient V.K. who suffered from damage to the posterior parietal lobe (Jakobson et al., 1991). More specifically, Patient V.K. suffered from bilateral hemorrhages in the occipitoparietal regions, resulting in optic ataxia

(Jakobson et al., 1991). Patient V.K.'s ability to perceive the objects presented to her by the researchers was completely intact, yet her ability to reach and grasp those objects was significantly impaired. Not only was patient V.K. able to perceive the objects, but she was also able to identify them and recognize their colours. Despite her intact perception, patient V.K. was unable to properly preshape her hand and finger in relation to the object's shape and size to successfully grasp the object (Jakobson et al., 1991).

Together, the findings from patient D.F. and patient V.K. led Goodale and Milner to theorize that the dorsal stream, which they named the "how" pathway, was responsible for processing visual information into the representations needed for visually guided actions, while the ventral stream, which they named the "what" pathway, was responsible for processing visual information into the perceptual representations of the world around us (Goodale & Milner, 1992; Milner & Goodale, 2006).

Reaching and Grasping Stationary Objects

Prehension is a seemingly simple action, so much so that many people consider it one movement (Smeets & Brenner, 1999; Mon-Williams, & McIntosh, 2000) when in fact, it consists of two separate movements (Jeannerod, 1981) with two different evolutionary origins (Karl & Whishaw, 2013), a reach movement and a grasp movement. The reach movement transports the hand in relation to the object's extrinsic spatial properties (position and orientation), whereas the grasp movement preshapes the fingers in relation to the object's intrinsic spatial properties (size and shape). When grasping stationary objects, the two movements are temporally integrated in a stereotypical fashion under feedforward visual guidance (Arbib, 1981; Haggard & Wing, 1998; Jeannerod, 1981; Smeets & Brenner, 1999). Given the versatility of the visuomotor behaviour, it is important to analyze how the brain utilizes sensory information to produce such complex actions in a seemingly simple fashion.

Eye movements are integrated into the motor patterns of every visually-guided action. More specifically, eye fixations are utilized to locate objects one wishes to act upon and determine the trajectory of movements needed to complete an action (Land et al., 1999; Land, & Hayhoe, 2001). Moreover, eye fixations are crucial for providing information about the location of the contacting hand, as that allows for making online corrections as needed (Binsted et al., 2001; Lünenburger et al., 2000; Riek et al., 2003). Where I fixate on an object is related to the task at hand. When reaching to grasp stationary objects, previous research suggests that gaze fixation occurs on the eventual contact point of the index finger (Brouwer et al., 2009; Desanghere & Marotta, 2011, 2015; Prime & Marotta, 2013; Voudouris et al., 2016). In contrast, when participants look at an object without having to act on it, they fixate on the center of mass (COM) of the object (Brouwer et al., 2009; Vishwanath & Kowler, 2003, 2004). Taken together, to successfully produce fluid and accurate reaching and grasping movements, information regarding the stationary object, as well as the hand, is needed.

Reaching and Grasping Moving Objects

Grasping moving objects adds even more complexity. To successfully grasp a moving object, such as a flying frisbee, a person must be able to predict the location at which one’s hand will encounter the moving frisbee. To do so, the person must focus on the frisbee prior to initiating the reaching and grasping movements and be able to anticipate its trajectory by ‘looking ahead’ in the eventual path of the frisbee. Anticipating the direction of the movement allows for a higher grasping success rate since there would be more time to reassess where the grasping hand is and adjust its location as needed, to intercept the trajectory of the frisbee. Not anticipating the location at which the hand will meet the object would lead to an increased risk of missing the object. Given how vastly complex our environment is, it is important to understand how the brain utilizes visual information to guide these complex behaviours.

Several research studies that have utilized moving three-dimensional (3D) objects give insight about the visual information needed to successfully intercept a moving object. For instance, Lopez-Moliner and colleagues (2010) occluded the vision of participants at various times during a trial of catching a slowly thrown ball. They identified two key moments during which visual information was crucial for successfully catching the thrown ball: when the ball is thrown and right before it is caught (Lopez-Moliner et al., 2010; Lopez-Moliner & Brenner, 2014). Those findings are in line with previous literature that suggest that to catch a moving object, one must be able to identify the trajectory of the object, as well as be able to make corrective movement to successfully intercept it (Montagne et al., 1999; Müller, & Abernethy, 2006; Müller et al., 2006). These results provide valuable insight into how the brain utilizes visual information to guide goal-directed behaviour.

Visuomotor Behaviour Directed at 2D Targets vs. 3D Objects

Analyzing how the brain produces movements towards moving objects using real three-dimensional objects is a reliable yet limiting option. It is difficult to manipulate the characteristics of the movement of the object and the environment in which it moves, such as the shape, size, speed, and direction of movement of the object, in a rigorously systematic way that is required for drawing appropriate conclusions. A reliable alternative to 3D objects are computer-generated two-dimensional targets (2D) presented to participants on a screen monitor.

Without a doubt, reaching to grasp a 3D object is a different experience from reaching to grasp a 2D target. 2D targets lack certain characteristics that 3D objects have, such as weight and texture. The literature suggests that the "realness" of an object being manipulated influences visual processing (Freud et al., 2018). Further support for the difference in visual processing when grasping 2D targets versus when grasping 3D objects comes from studies that suggest that grip apertures adhere to Weber's law when grasping 2D targets, but not when grasping 3D objects (Ozana & Ganel, 2019; Ozana et al., 2020). Weber's law refers to the "phenomenon in perception that the just-noticeable difference in a physical property is a fixed proportion of its magnitude" (Smeets & Brenner, 2008, p. 1089). Despite all these differences between 3D and 2D grasping, there are some visuomotor behaviour similarities in manipulating 3D objects and 2D targets. Recent research studies show that certain behavioural features, such as eye-fixation position and digit placement are similar when reaching-to-grasp a 2D object and a 3D object (Bulloch et al., 2015; Langridge & Marotta, 2017, 2021; Thulasiram et al., 2020). Taken together, utilizing computer-generated 2D targets to analyze fixation behaviour, among other kinematic measures, can produce reliable results.

Anticipatory Oculomotor Behavior and Moving Targets

To successfully execute a goal-directed action, consistent visual feedback of the target is crucial. Langridge and Marotta (2017) conducted a study to examine the effects of occluding a moving target, after its movement has been initiated, on the participants' ability to successfully grasp that target. Results showed that participants did not successfully grasp the occluded object, suggesting that they were unable to extrapolate the movement of the target from the information obtained at the onset of the movement of the object, prior to its occlusion. Moreover, results showed that the placement of the index finger and the final horizontal gaze position consistently occurred behind the center of mass of the target (Langridge and Marotta, 2017). These findings are incongruent with the previously discussed findings that suggest that index finger placement and final gaze position occur, on average, at the center of mass of stationary targets. Given how important continuous visual feedback of a moving target is, it is important to investigate the active process embarked on by the visual system to acquire the necessary information to successfully complete a goal-directed behaviour (Henderson, 2003).

When the direction of a moving target is known, people tend to focus ahead on the leading edge of the target, even prior to the movement onset of that target. Bulloch *et al.* (2015) conducted a study to examine the effects of manipulating the direction of movement of two-dimensional targets on gaze behaviour. To do so, a horizontally moving 2D target was programmed to either move from the leftward edge of the screen towards the rightward edge or vice versa. Participants were asked to reach and grasp the target once they hear a “go” tone. Results revealed that participants fixated about 7.1 cm ahead of the leading edge of the target, prior to the onset of the movement of the target and the reaching and grasping movements (Bulloch et al., 2015). The researchers attributed these results to participants’ attempts to eliminate the “cognitive effort” that must be exerted to catch up to and continue following a target that has already begun moving (Bulloch et al., 2015). Similar results were observed in a study that utilized vertically moving two-dimensional targets (Thulasiram et al., 2020). Thulasiram and colleagues (2020) asked participants to reach and grasp 2D vertically moving objects that moved from the top to the bottom of the screen monitor or vice versa. Results revealed that participants made anticipatory fixations in the direction in which the object was going to move in (Thulasiram et al., 2020). The consistent findings shed light on the importance of making anticipatory fixations when reaching to grasp moving objects. Previous research suggests that anticipatory fixations can be thought of as one of the steps in the planning phase that increases the chances of successfully manipulating a moving object as one may wish

(Mennie et al., 2007). Given how advantageous anticipatory fixations can be, it is important to investigate in which contexts do they occur, and how much various factors, such as environmental statistics, can influence them.

There is a growing body of evidence that suggests that statistically regular events in our environment lead to the production of anticipatory behaviour. Notaro and colleagues (2019) conducted a study to investigate the influence of input statistics on anticipatory behaviour, using a statistical learning paradigm. The paradigm involved a target that would either be displayed towards the right side or the left side of a screen monitor. Participants were asked to make a rapid eye-movement (saccade) towards the target regardless of where it is shown. Depending on the condition, the probability of the location of the target was manipulated so that the target was displayed on the same side as the previous target either 70% of the time or 30% of the time (Notaro et al., 2019). Prior to being presented with the target, participants were presented with a fixation symbol that appeared for 400 ms, then a post-fixation blank screen that appeared for 160 ms. The researchers chose anticipatory fixation offsets during the last 10 ms of the post-fixation blank screen as the anticipatory behaviour of interest. Results revealed that oculomotor behaviour, such as anticipatory fixation offsets, is strongly influenced by statistical input from the environment (Notaro et al., 2019). These findings are interesting as they engage a bigger, deeper question: how much of our behaviour is influenced by the statistical probabilities of our environment, of which, I may not be conscious? The visuomotor system produces simple movements that constitute the basis of our interactions with our environment: reaching and grasping. Therefore, the question must be asked, is the visuomotor system sensitive to environmental statistics?

Directional Bias

As mentioned earlier, this study aims to investigate the effects of directionality bias on anticipatory behaviour. The existence of anticipatory behaviour would serve as an indication that the visuomotor system is sensitive to directionality bias. In such a scenario, if a target appears in the middle of a screen and moves towards the left more often than it moves towards the right, an anticipatory fixation would occur towards the leftward leading edge of a target, prior to its movement onset. Although, these results indicate that the anticipatory fixation occurred solely because of the directional bias, previous research may suggest otherwise.

Several studies have found that participants tend to display a leftward bias when acting upon moving two-dimensional targets. Bulloch and colleagues (2015) found that when a target appears on the most rightward edge of a screen monitor and moves leftwards, participants tended to fixate further ahead of the target’s leading edge as opposed to when a target appears on the most leftward edge of a screen monitor and moves rightwards. Similarly, Langridge and Marotta (2017) found that when grasping two-dimensional moving targets, participants consistently placed their index finger towards the left of the center of mass of the target, regardless of its direction of movement. These behaviours may have occurred due to the crossbody mechanical constraints that occur when a person is reaching towards a leftward moving object with their right hand (Brenner & Smeets, 2007; Bulloch et al., 2015; Langridge & Marotta, 2017).

In addition, these observed behaviours could be attributed to the phenomenon known as pseudoneglect. Pseudoneglect refers to the tendency of neurologically healthy individuals to favour processing stimuli presented in their left hemifield over stimuli presented in their right hemifield (Bowers & Heilman, 1980; Jewell & McCourt, 2000). Bowers and Heilman (1980) found that when participants are asked to bisect a line presented to them, they tend to bisect the line leftward to the center rather than at the true center. Based on their findings, Bowers and Heilman (1980) coined the term “pseudoneglect.” The line bisection test was proposed by Schenkenberg and colleagues (1980) and has become a standard perceptual task of pseudoneglect. More recently, Chiffi and colleagues (2021) conducted a study to examine the correlation between pseudoneglect as observed during the completion of a line bisection test versus the visuo-spatial attentional asymmetries observed during the completion of free visual exploration tasks. This study showed that the pseudoneglect observed in the results of a line bisection test are correlated with the average gaze position during certain time periods of visual exploration in a free visual exploration task. Such findings indicate that the line bisection task is a reliable tool which could be used to correlate pseudoneglect that occur in different contexts.

Pseudoneglect is not only demonstrated using the line bisection task; several studies demonstrate that pseudoneglect can be observed during visual search tasks. For instance, Nicholls and colleagues (2014) conducted a study to investigate if pseudoneglect can be observed during conjunctive visual search tasks. Results showed that targets presented in the participant’s left hemifield were detected faster and with less errors than targets presented in the participant’s right hemifield (Nicholls et al., 2014). These findings demonstrate that not all objects in our environment are being attended to equally, highlighting the complexity of the processes that guide visuomotor behaviour.

As mentioned earlier, pseudoneglect is observed in a wide range of perceptual tasks. However, previous research suggests that a considerable amount of variation and inconsistencies exist between various studies and tasks (Jewell & McCourt, 2000; Strauch et al., 2022). For instance, in a wide variety of perceptual task, consistent rightward bias has been observed (Benwell et al., 2013; Tomer, 2008). Some studies have found that up to approximately 50% of their participants displayed rightward bias on line bisection tasks, rather than the expected leftward bias (Braun & Kirk, 1999; Cowie & Hamill, 1998). For instance, Szczepanski and Kastner (2013) conducted a study which utilized a modified landmark task which is a perceptual task that does not have the motor requirement of the line-bisection task. Forty-six participants were shown pre-bisected lines of varying lengths and were asked to identify which side is longer. Results revealed that roughly 13.04% of participants had a rightward bias that was 1 standard deviation (SD) above the mean; 15.22% of participants had a leftward bias that was 1 SD above the mean; 71.74% of participants had biases less than 1 SD away from the mean to the right or the left (Szczepanski & Kastner, 2013). More generally, Szczepanski and Kastner (2013) found that on average, participants displayed a slight rightward bias, rather than the expected leftward bias which has been reported by ample studies that utilized perceptual tasks, such as the line-bisection task and landmark task. These conflicting results clearly suggest that the neural mechanisms which give rise to pseudoneglect and visual attention, more generally, are not fully understood.

Visual Attention

To date, there has been little agreement on the neural underpinnings of pseudoneglect, or the asymmetrical allocation of attention towards the left visual field that humans tend to exhibit. This is largely attributed to the mixed, often contradictory, findings that various studies obtain by conducting similar experiments, as has been demonstrated in the previous section. This section will examine the widely supported theories in the literature on visual attention and discuss those in relation to the neural mechanisms of pseudoneglect.

One of the most widely supported theories regarding pseudoneglect is the hemispheric asymmetry theory. The hemispheric asymmetry theory suggests that visuospatial attention is a bilateral function, with the right hemisphere having dominance of this function (Mesulam, 1981). Support for this theory arises from findings showing that stimulus factors that affect the magnitude and direction of neglect on line bisection task performance similarly affects the magnitude and direction of pseudoneglect on the same test, suggesting that both phenomena are modulated by the same attentional networks/ brain hemisphere (McCourt & Jewell, 1999). Hemispatial neglect is a disorder that arises predominantly from damage to the right parietal cortex, and is characterized by an inability to attend to stimuli in the contralesional visual field (Heilman et al., 2000; Marotta et al., 2003). McCourt and Jewell (1999) investigated the congruency of performance on line bisection tasks for pseudoneglect and neglect. They found that factors of the line bisection task such as line length, line aspect ratio, and azimuthal line position have the same effect on pseudoneglect and neglect. However, line elevation had an incongruent effect on neglect and pseudoneglect, meaning that it did not have the same effect on both participants with neglect, and healthy participants (McCourt & Jewell, 1999).

Furthermore, support for the hemispheric asymmetry theory comes from studies that directly compared healthy individuals when completing a line bisection task and a landmark task without any manipulation and while receiving continuous theta burst stimulation (cTBS) to the left or right angular gyrus via Transcranial Magnetic Stimulation (TMS). Varnava and colleagues (2013) conducted this study and found that if a person displays pseudoneglect (leftward bias), they are more likely to display patterns of left neglect (rightward bias) when they receive cTBS to their right parietal cortex, more specifically, the right angular gyrus. This finding suggests the commonality of the neural mechanisms giving rise to pseudoneglect and neglect. Moreover, Thiebaut and colleagues (2011) found a larger parieto-frontal network in the right hemisphere than the left hemisphere, suggesting the lateralization of this network to the right hemisphere. In addition, they found a significant correlation between the anatomical lateralization of that network and the degree of asymmetry observed in line bisection task performance (Thiebaut et al., 2011). Taken together, there is an abundance of evidence supporting the hemispheric asymmetry theory, which suggests that the pseudoneglect observed in healthy participants is largely due to the dominance of the right hemisphere in visuospatial attention functions.

Despite the robustness of the results supporting the hemispheric asymmetry theory, some studies contradict its premises. For instance, Heilman and Van Den Abell (1980) investigated the dominance of each hemisphere when completing a visuospatial task and found that most, but not all participants, had right hemisphere dominance. Because this finding clearly highlights the shortcoming of the hemispheric asymmetry theory, other theories of visuospatial attention were proposed to fill this gap. For example, the interhemispheric competition theory (Cohen et al., 1994).

The interhemispheric competition theory postulates that both hemispheres reciprocally inhibit each other while directing attention towards the contralateral field of vision (Cohen et al., 1994). Simply put, this theory suggests that one attention mechanism leads each hemisphere to simultaneously disengage attention from the opposite hemisphere *(competes with the opposite hemisphere)* while directing attention towards its contralateral visual field. Through their computational model, Cohen and colleagues (1994) suggested that only when the model is damaged or lesioned, a "disengage deficit" is produced. This deficit yields similar deficits that are observed in patients suffering from hemispatial neglect caused by unilateral parietal region damage. More specifically, hemispatial neglect symptoms arise because the damaged unilateral parietal region fails to direct attention towards the contralateral field of vision, while simultaneously failing to inhibit the other hemisphere, leading to significant visual bias or neglect. In addition, studies utilizing various imaging techniques have found the frontoparietal areas generate spatial bias towards the contralateral visual field, with the sum of the activation of that area determining the level of bias directed towards the contralateral visual field (Szczepanski et al., 2010; Szczepanski & Kastner, 2013). The level of activation in each hemisphere was found to be predictive of the level of bias revealed on perceptual tasks, such as the landmark task. Furthermore, obstructing the activation of the frontoparietal areas using transcranial magnetic stimulation (TMS) was found to decrease visual attention towards the contralateral visual field, and increase bias towards the ipsilateral visual field (Szczepanski & Kastner, 2013).

The hemispheric asymmetry theory and interhemispheric competition are somewhat interchangeable. Therefore, some findings could be interpreted differently to support either theory. For instance, Wang and colleagues (2023) conducted a meta-analysis of 18 studies that utilized TMS to inhibit the left or right posterior parietal cortices (PPC) for a total of 222 participants. The purpose of this meta-analysis was to explore the effects of inhibitory TMS on the aforementioned areas on attention biases revealed during the completion of landmark and line bisection tasks. Results of the analysis revealed a shift in bias towards the right visual field following TMS inhibition of the right PPC, but no shift in bias following TMS inhibition of the left PPC (Wang et al., 2023). Ultimately, the authors were not able to make a definitive decision in regard to which theory is significantly supported by this data. They argued that although this data could easily be interpreted as supportive of the hemispheric asymmetry theory because distortions in visual attention were only observed when the right PPC, but not the left PPC, was suppressed. However, the authors argued that these findings could also be interpreted as supportive of the interhemispheric competition theory because suppressing the right PPC could have led to the disinhibition of the left PPC which resulted in the shift in bias towards to the right visual field (Wang et al., 2023). This meta-analysis highlights the challenge of understanding the neural underpinnings of visual attention as similar data sets could support opposing theories.

In conclusion, the neural mechanisms controlling visual attention and their way of operation remain a controversy. The two theories of visual attention discussed in this section, are two of many theories of visual attention. For instance, Corbetta and Shulman (2011) argued that hemispatial neglect arises due to disruption of cortical neural networks, rather than specific brain regions, suggesting a broader view of the control of visual attention instead of focusing on the two hemispheres. Findings of the current study will be discussed considering the various theories of visual attention.

The Current Experiment

Although previous research suggests that statistically regular events lead to the production of anticipatory oculomotor behaviour, it remains unknown whether the visuomotor system is sensitive to the manipulation of the direction of a moving target. The purpose of the present study was to investigate the visuomotor system’s ability to utilize directionality bias of a moving target from its movement history. Participants were required to reach and grasp a horizontally moving target. Each trial consisted of the target appearing in the middle of the screen and translating horizontally either towards the right or the left. The horizontal movement of the target was manipulated so that in most trials, the target moved towards one side more than the other, creating a directionality bias. A secondary goal of this study was to compare spatial asymmetries in a visuomotor task and a perceptual task, such as the line bisection test. Therefore, in addition to this visuomotor task, participants completed two line-bisection tests, once prior to completing the visuomotor task described and once after completing the visuomotor task.

Hypotheses

Visuomotor Task

Based on the literature demonstrating the anticipatory behaviour of the oculomotor system, it was reasonable to predict that the visuomotor system will be sensitive to the directionality bias of a moving target, leading to production of anticipatory behaviour, increasing one's chances of successfully grasping that target.

More specifically, I hypothesized that when participants complete no-directionality-bias trial blocks (target moves 50% towards right and 50% towards the left), while the target is stationary, participants would fixate towards the center of mass of the target, as observed in Desanghere and Marotta (2011). However, in the directionality-bias trial blocks (target moves 75% towards one direction and 25% in the opposite direction), I hypothesized that participants would fixate towards the anticipated leading edge of the target while the target is stationary. For instance, participants in the right-directionality-bias group (target moves 75% towards right and 25% towards the left) would fixate towards the right edge of the target prior to the onset of its movement. This hypothesis was based on the findings of the study conducted by Notaro and colleagues (2019) that suggest that statistically regular events lead to the production of anticipatory behaviour. Finally, in all conditions, I hypothesized that once a target begins moving, participants would fixate towards the leading edge of the target as observed in the studies conducted by Bulloch and colleagues (2015) and Thulasiram and colleagues (2020).

In addition to the anticipatory behaviour being measured, learning effects were analyzed. I hypothesized that as participants complete more "directionality-biased" trials, the anticipatory behaviour would increase in magnitude, suggesting that learning has taken place. For instance, as participants completed more trials in the directionality-biased blocks, they would begin fixating further away from the midline of the target, towards the anticipated leading edge of the target while the target is still stationary.

Line Bisection Task

I hypothesized that there would be no significant difference in the scores of the first line bisection test (pretest) between participants in the rightward directionality bias group and participants in the leftward directionality bias group. However, I hypothesized that within each group, performance on line bisection test 1 (pretest) would be significantly different from performance on line bisection test 2 (posttest). In addition, I hypothesized that on the posttest, participants in the rightward directionality bias group would display a weaker effect of pseudoneglect, in comparison to the leftward directionality bias group, if any, because of the rightward bias that was established in the visuomotor task carrying over to the perceptual task. Similarly, participants in the leftward directionality bias group would display a stronger effect of pseudoneglect than participants in the *rightward* directionality bias due to the carryover effects of the *leftward* directionality bias established in the visuomotor task.

CHAPTER II

GENERAL METHODOLOGY

The purpose of these experiments was to examine the visuomotor system's sensitivity to directionality bias. Moreover, I aimed to investigate the possible effects that introducing directionality bias in a visuomotor task could have on performance during a perceptual task.

At the beginning of the study, participants completed a line bisection test. Afterwards, participants were asked to perform precision grasping movements towards a moving two-dimensional target. The target consisted of a grey rectangle block that appeared on a black background in the middle of the screen at the beginning of each trial and moved horizontally either towards the right or to the left. Following this visuomotor task, participants completed a second line bisection test. This study was approved by the Research Ethics Board at the University of Manitoba, Ft. Garry Campus.

Participants

Forty-eight right-handed participants (25 female; aged from 17 to 34, mean age 20.1 years), were recruited from the student body at the University of Manitoba. Only participants with normal vision or corrected to normal vision were permitted to participate due to limitations of the eye-tracker. Participants were compensated for their participation in one of two ways, depending on their enrollment status. Participants who were enrolled in PSYC1200: Introduction to Psychology received three credits towards their Introduction to Psychology class. Participants who were not enrolled in the PSYC1200 class received a $10 Starbucks gift card. Random assignment was achieved through the randomized slot allocation method. This method involves the pre-allocation of a condition to a specific timeslot, providing all eligible individuals with an equal opportunity to sign up.

Only individuals whose native reading language is English were allowed to participate in this study. This was done as several studies have suggested that scanning direction influences results of the line bisection task (Bowers, & Heilman, 1980; Chokron et al., 1998). For example, individuals whose native reading language is read from right to left display weaker leftward bias or no leftward bias at all on pseudoneglect tasks (Smith et al., 2015).

Materials and Procedure

Each data collection session began with participants receiving and signing a consent form detailing information regarding the study. Participants then completed a brief questionnaire regarding their age, sex assigned at birth, visual acuity, and native reading language. In addition to the demographic questionnaire, participants completed a modified version of the Edinburgh Handedness Inventory (Oldfield, 1971; Appendix A) to ensure that they were right-handed.

Participants were seated on a height-adjustable chair and asked to place their chin in a chinrest, positioned 50 cm away from the screen monitor on which the targets were presented. Participants had the ability to adjust the height of their chair as needed, to ensure their comfort while their chin was placed in the chinrest. The screen monitor utilized in this experiment was 52.70 cm in width and 29.64 cm in height, with a resolution of 1080p and a refresh rate of 60 Hz.

After adjusting the height of the seat to their comfort, participants were asked to complete the line bisection task (Schenkenberg et al., 1980). The line bisection task consisted of twenty lines arranged randomly on an A4 sheet of paper. The page was taped on the desk in front of the participant along their mid-sagittal axis. The line bisection task consisted of eight lines positioned in the center of the page, six lines positioned on the left side of the page, and six lines positioned on the right side of the page. The top and bottom lines were 150 mm long and appear in the middle of the page. These two lines were used for training, which the experimenter used to show the participants how to complete the task. Using a pencil, participants were asked to determine the midpoint of the line by drawing a vertical dash on each of the eighteen middle lines. Participants were instructed to mark each line in order, from top to bottom, without skipping any lines. In addition, participants were told that once they place a dash to indicate the midpoint of a line, they were not allowed to erase it or fix it in any way. The eighteen experimental lines were grouped in six groups of three line, with each group having a different length. The six lengths corresponding to each one of the six groups are: 100 mm, 120 mm, 140 mm, 160 mm, 180 mm, and 200 mm. Within each group of three lines, each line had a different orientation: left side, right side or middle (Appendix B). This was done to control for the position of line on the page when measuring deviations from the true center of each line. A similar setup was utilized by several previous studies (Chiffi et al., 2021; Kwon et al., 2020; Schenkenberg et al., 1980). Although motor action is required while completing the line bisection task (marking the midpoint of each line using a pencil), the line bisection task measures perceptual judgement since the motor action is only a report of the conscious percept (Haffenden & Goodale, 1998).

Completion of the line bisection task was immediately followed by the visuomotor task. To track their right hand, head, and eye movements, participants were fitted with nine infrared light-emitting diodes (IREDs), and a EyeLink II head-mounted eye-tracking system (250 Hz sampling rate, spatial resolution <.05 deg; SR research Ltd., Mississauga Ontario, Canada). Two IREDs were placed on the index finger, two on the thumb and two on the distal radius of the wrist. The four IREDs for the index finger and thumb were placed 0.50 cm away from the fingertips. Three IREDs were placed on the EyeLink II headset to track the movements of the head. Movements were captured using an Optotrak Certus 3-D motion tracking system (100 Hz sampling rate, spatial accuracy up to .01 mm; Northern Digital Inc., Waterloo, Ontario, Canada). Gaze position was recorded by the EyeLink II head-mounted eye-tracking system. The eye-tracking system was calibrated using a 9-point calibration system. Since the EyeLink II head-mounted eye-tracking system and the Optotrak Certus 3-D motion tracking system recorded at two different frequencies, data produced by these two systems were integrated using MotionMonitor xGen software (Innovative Sports Training Inc., Chicago Illinois, USA).

Additionally, MotionMonitor was utilized to align the gaze and grasp positions into a common frame of reference for analysis.

The visuomotor task consisted of six blocks, with 16 trials in each block. Prior to the start of each block, an Eyelink calibration check was conducted to ensure the proper calibration of the eye-tracking system. For the calibration check, participants were asked to fixate on a centrally located dot on the screen for 10 seconds. Acceptable error ranges are 0.5 cm or less for the X-coordinate and 1.0 cm or less for the Y-coordinate. If the Eyelink calibration check indicates larger error rates, outside of the acceptable error margins, the Eyelink was recalibrated before advancing to the next block of trials. Similar error ranges have previously been utilized by Langridge and Marotta (2017; 2020; 2021) and Bulloch and colleagues (2015).

The computer-generated two-dimensional target was generated using MotionMonitor xGen software. The target was 7 x 3.5 cm in size (8.02 deg x 4.01 deg), grey in colour and moved at a speed of 15 cm/s (17.19 deg/s). The target appeared in the middle of the screen and was programmed to move horizontally towards either the right or the left, depending on the trial. In this manipulation, I ensured that the target appeared at or below the participant's eye level for two reasons. First, I wanted to ensure that this task emulates natural daily activities where most objects that a person interacts with would be at or below their eye level. Second, previous research suggests that directing attention towards upper visual space increases the activation of the right-hemisphere, possibly leading to an increased attentional bias towards the left visual field (Thomas et al., 2015). To ensure that the target behaved in a manner like a moving three-dimensional object, the target was programmed to stop its movement once the distance of one of the two IREDs placed on the index finger reached 0.50 cm from the screen. Since the IREDs were placed approximately 0.50 cm from the tip of the index finger, the target stopped at nearly the same moment the index finger touched the screen, mimicking a real 3D moving object that halts when grasped.

At the beginning of the visuomotor task, participants were given four training trials to ensure their understanding of the task, and to allow them to ask questions, if needed. Participants were directed to grasp the target “as quickly and as naturally as possible.” In addition, participants were instructed to place their right hand on the same starting point on the desk that was placed 35 cm away from the screen monitor, in the ‘start position.’ The start position consisted of pinching the thumb and index finger together, with the middle, ring and pinky finger fixed. Participants put their hand in the ‘start position’ following each trial, in preparation for the subsequent trial.

Each trial began when the block appeared. The block remained stationary in the middle of the screen for approximately 2.5 seconds. After 2.5 s, the block began moving horizontally. After 3 seconds from the beginning of the trial, a 450 Hz tone was played for a duration of 250 ms. The tone served as a ‘go’ signal that directed the participant to reach and grasp the moving target. The timing of the tone was manipulated in distractor trials, so that the tone was played once the objects starts moving. Distractor trials were added to increase variability between trials to ensure that participants remained attentive throughout the entire study. These distractor trials are called “timing distractors.” Once the participant grasped the target, the target stopped in the position in which it was grasped for 2 seconds then it disappeared, indicating the end of the trial.

Once the visuomotor task was completed, all equipment was removed. Then, participants completed a second line bisection test that was exactly like the one completed at the beginning of the experiment. Once the second line bisection task was completed, participants received a debriefing form that outlined the purpose of the study.

Experimental Design

Visuomotor Task

The visuomotor task utilized a mixed factorial design. Participants were randomly assigned to one of two groups, a rightward bias group or a leftward bias group. Regardless of their group, all participants completed two blocks of no-directionality bias first (Within-subject variable). Then, directionality bias was introduced in the subsequent four blocks that participants completed (Between-subject variable). The directionality bias differed for participants depending on the randomly assigned group.

Participants completed at total of six blocks of trials. The first two blocks were the no-directionality bias blocks. This means that 50% of the trials involved the target moving towards the right and the other 50% of trials involved the target moving towards the left. Subsequently, a participant assigned to the rightward bias group completed four rightward bias blocks, whereas a participant assigned to the leftward bias group completed four leftward bias blocks. In the right-ward bias blocks, the target moved 75% to the right and 25% to the left. In the left-ward bias blocks, the target moved 75% to the left and 25% to the right.

In each of the "no-bias" blocks (Block 1 and Block 2), there were 12 experimental trials (6 leftward moving & 6 rightward moving) and 4 timing distractor trials (2 leftward moving & 2 rightward moving). In each of the "biased" blocks (Blocks 3, 4, 5, and 6), there were 12 experimental trials, 9 of them moved in either the right or left direction, depending on the group, while the remaining 3 trials moved in the opposite direction. In addition, there were 4 timing distractor trials in the biased group conditions. In 3 of those timing distractor trials, the target moved towards the direction of the bias and in the remaining trial, the target moved in the opposite direction.

The order in which the trials are organized was pseudorandomized. I chose a pseudorandom order instead of a true random order because a randomization tool may have produced an order than includes too many consecutive trials moving in the non-biased direction. Two rules were adopted when creating the order of trials within each block. For Block 1 & Block 2 (the “no-bias” blocks), a max of two consecutive trials were allowed to move in the same direction. For Blocks 3, 4, 5, & 6 (the “biased” blocks), trials moving in the ‘non-biased’ direction were not allowed to appear consecutively. Therefore, to create the order of trials while following these rules, I created the order using a randomization tool, and then adjusted the order of trials if they violated the rules.

Line Bisection Task

Like the visuomotor task, the line bisection task utilized a mixed factorial design (Left vs Right Directionality Bias: Between-subjects variable, Pretest vs. Posttest: Within-subjects variable). Participants completed two-line bisection tests, once prior to completing the visuomotor task (line bisection test 1) and once afterwards (line bisection test 2).

Data Analysis

Visuomotor Task

Variables

The independent variable in the visuomotor task was the biased horizontal direction of the target’s movement. The dependent variables for the visuomotor task consisted of eye fixations at five different timepoints of interest. Fixations were determined based on the dispersion-threshold identification (I-DT) algorithm (Salvucci & Goldberg, 2000). Specifically, a fixation was defined as a pause in eye movements for at least 100 ms, with a maximum dispersion threshold of 1 cm. ***Fixation 1*** was the first intentional fixation occurring after the appearance of the target. To ensure the fixation being included in the analysis was in response to the appearance of the target, Fixation 1 was defined as the fixation occurring around 200 ms after the appearance of the target. This reaction time was determined based on the literature suggesting that reflexive saccades occur around 200 ms (Hutton, 2008). ***Fixations 2 & 3*** were the fixations that contain the timestamps 1.00 s and 2.00 s, respectively. ***Fixation 4*** was the first intentional fixation occurring after the onset of movement of the target. Finally, ***Fixation 5*** was the first intentional fixation occurring after the tone was played, cuing the participants to begin reaching towards and grasping the target. Like Fixation 2, Fixations 4 & 5 were defined as the fixation occurring around 200 ms after the event of interest has taken place (onset of movement for Fixation 4 & tone being played for Fixation 5). These fixations were measured in relation to the position of the target. Using MotionMonitor xGen, eye movement data were analyzed to determine fixation position coordinates.

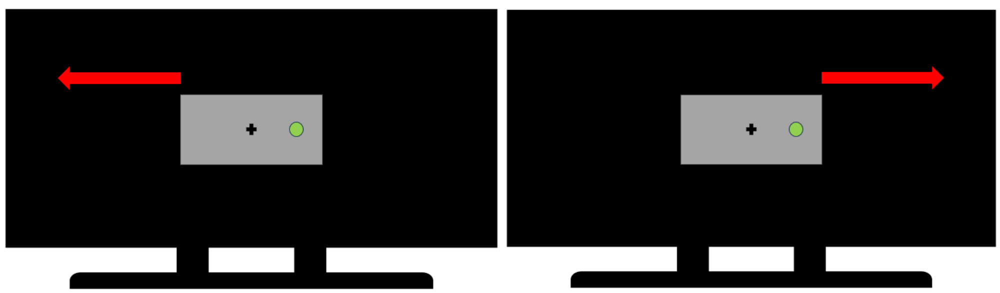
Data Setup

As mentioned earlier, fixations were measured in relation to the position of the target. Given that in each trial, the target appeared in the middle of the screen, and translated horizontally either towards the left or the right, calculations for fixations had to be made in a standardized way to ensure that the viewpoint is maintained regardless of the direction of the movement of the target. In this context, viewpoint means ahead of the center of the target or behind it. I chose to standardize my calculations so that a negative value for a fixation is indicative of a fixation that is ‘trailing’ the center of mass of the target. Whereas a positive value for a fixation is indicative of a fixation that is ahead of the center of mass of the target.

To achieve this standardized way of calculating each fixation, different formulas had to be used for calculating fixations in rightward moving trials and in leftward moving trials. The system was set up so that the bottom left corner of the screen was the origin of the world axis (x, y, z: 0, 0, 0). In this set up, positive x-axis faced the right, and positive z-axis faced upwards. Therefore, for rightward moving trials, fixations were calculated as "Fixation – Target Location" whereas, for leftward moving trials, fixations were calculated as "Target Location – Fixation." By calculating fixations differently, depending on the trial, I ensured that fixations trailing the center of the target were in negative values while fixations made ahead of the center of the target were in position values (see Figure 1 for a visual illustration).

Figure 1

Figure illustrating two trials in Block 1



Note. This is an example of two trial blocks, a leftward moving trial (left figure), and a rightward moving trial (right figure) – as illustrated by the red arrows. In both trials, the target has not begun moving yet, and the cross is illustrating the true midpoint of the target, measured at 0.2635 m *(cross is not displayed to participants)*. Green dots illustrate an example of fixations, both dots are shown at 0.30 m – in relation to the world axis. In the leftward trial, the fixation would be measured as "Target Location – Fixation" = 0.2635 – 0.30 = -0.0365. This means that even though that the target has not begun moving yet, the fixation ***trails*** the center of the target by 0.0365 m. In the rightward moving trial, the fixation would be measured as "Fixation – Target Location" = 0.30 –

0.2635 = 0.0365. This means that even though the target has not begun moving yet, the fixation is ***ahead of*** the center of the target by 0.0365 m.

Statistical Analysis

Not all trials completed by participants were included in the analysis for this study. For Blocks 1 & 2 (unbiased blocks), all 12 experimental trials were averaged out in each block for every participant, six rightward moving trials, and six leftward moving trials. For Blocks 3, 4, 5, & 6 (biased blocks), only the 9 trials where the target moved towards the biased direction were included. The 3 remaining experimental trials where the target moved against the biased direction were not included in the analysis as they served as trials that maintain 75%-25% directional bias but were not meaningful in answering the questions asked in this study.

For each dependent variable, the experimental trials from each of the six blocks were averaged out to create a condition mean per block, per participant. This was done to ensure that if learning had taken place as participants completed more trials, the analysis would reveal the learning effect by comparing the means of each block of trials. In addition, if any learning effects were observed, conducting the analysis this way allowed us to specify the stage of the experiment during which learning began to occur. If learning were to take place, I would expect to observe a larger effect of directionality bias on anticipatory behaviour. This means that the anticipatory fixations participants perform would be skewed more towards the leading edge of the target with each subsequent block of the directionality bias trial blocks. A 2 (directionality bias: leftward or rightward) x 6 (trial block: block 1, block 2, block 3, block 4, block 5, & block 6) mixed analysis of variance (ANOVA) was conducted, with directionality bias as a between-subjects factor, and trial block group as a within-subject factors on each dependent variable.

Line Bisection Task

Variables

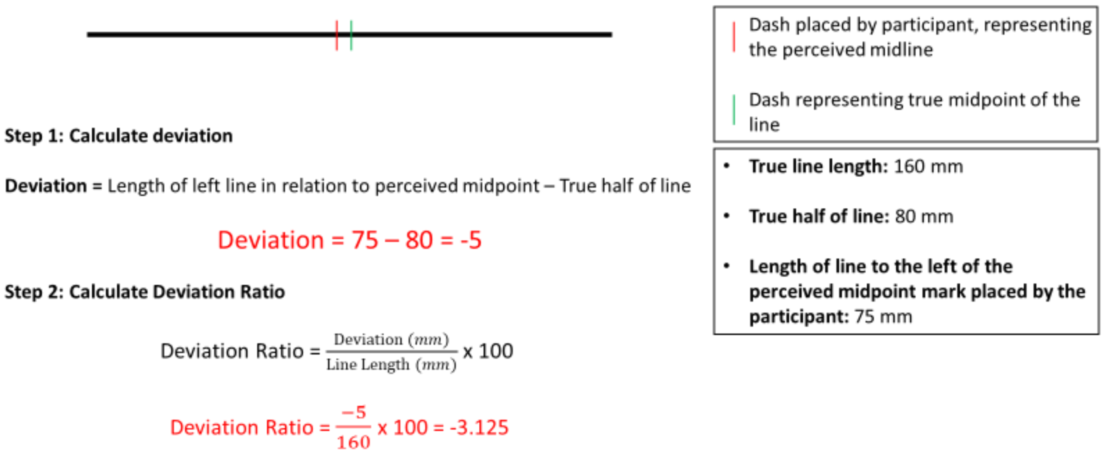
The independent variable in the line-bisection task is the directional bias introduced in the visuomotor paradigm participants completed. The dependent variable is the average deviation from the center of each of the 18 experimental lines in each test. To obtain the average deviation from the true center of each line in a comparable manner, deviations were calculated as proportion of the line (deviation ratio), so the length of each line is taken into consideration. This procedure involves calculating the length of the line to the left of the perceived midpoint mark placed by the participant to the nearest half millimeter. From there, the true half of the line was subtracted from the measured left half. This was done so that a positive score would indicate that the mark placed by the participant was to the right of the true center. Whereas a negative score would indicate that the mark placed by the participant was to the left of the true center. Then, using the following formula, a standardized deviation ratio score was obtained:

$$\text{“Deviation Ratio} = \frac{\text{Deviation } (mm)}{\text{Line Length } (mm)} \text{ x } 100\text{”}$$

By obtaining the deviation ratio of each of the 18 experimental lines, I was able to obtain one score by taking the average of all deviation ratios in each test. The following figure presents the method by which the line-bisection task was analyzed. See Figure 2 for a summary of this method.

Figure 2

Steps taken to obtain the deviation ratio for each of the 18 experimental lines on the line-bisection task.



Note. Line length is not to scale.

Statistical Analysis

A 2 (directionality bias: leftward or rightward) x 2 (Test: line bisection test 1 [pre-test] & line bisection test 2 [post-test]) mixed analysis of variance (ANOVA) was conducted to measure the effect of the bias introduced during the visuomotor task on performance during the perceptual task utilized in this study, the line bisection test. For this test, directionality bias direction is the between-subject factor, and test timing is the within-subject factor (pre-test vs post-test).

CHAPTER III

RESULTS

Visuomotor Task

Excluded Data

Experimental data were excluded from analyses if the participant executed the task incorrectly (i.e., initiated the reach prior to the presentation of the tone or failed to grasp the target prior to its movement off the screen) or if data was lost due to equipment failure. A final tally of the trials revealed that 6.10% of trials were excluded due to one of these two reasons.

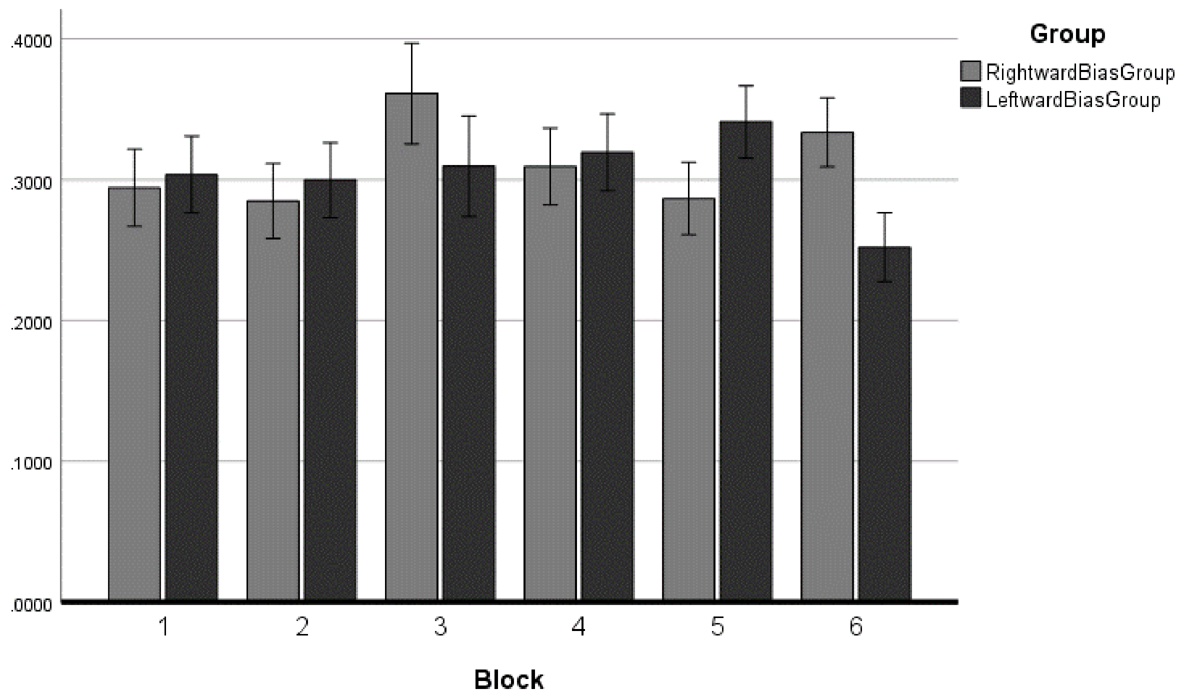
Fixation Measurement Accuracy

Accuracy checks were conducted at the beginning of each block to ensure that the observed error for the horizontal axis was lower than 0.5 cm. If the observed error rate was larger than 0.5 cm, a recalibration and validation of the Eyelink system was completed, and another accuracy check was conducted prior to the resumption of the study. The average absolute error combined among all participants, and across all blocks, was 0.30 cm in the horizontal axis. Average absolute error is defined as the absolute value of observed error rate obtained at the beginning of each block, averaged out. For the average absolute error rate of each group per Block, please see Table 1. The average displacement error for all participants, across all six blocks, was 0.04 cm (SE = 0.028) to the left of the center of the target. The average displacement error for participants in the leftward bias group, across all six blocks, was 0.08 cm (SE = 0.041) to the left of the center of the target. The average displacement error for participants in the rightward bias group, across all six blocks, was 0.0002 cm (SE = 0.037) to the left of the center of the target. The average displacement error is defined as the value of observed error rate obtained at the beginning of each block, averaged out. For the average displacement error rate of each group per Block, please see Table 2.

In order to ensure that there were no significant differences between groups or within blocks for the absolute error rate of the accuracy check, a 2 (Directionality Bias Group: leftward or rightward) x 6 (Trial Block: block 1, block 2, block 3, block 4, block 5, & block 6) mixed analysis of variance (ANOVA) was conducted, with directionality bias as a between-subjects factor, and trial block group as a within-subject factors on each dependent variable. The results, displayed in Figure 3, indicated no significant main effect of directionality bias group on absolute error rate, $F(1, 46) = 0.103$, $p = 0.750$, $\eta_p^2 = 0.002$; no significant main effect of trial block on absolute error rate, $F(3.86, 177.47) = 0.877$, $p = 0.476$, $\eta_p^2 = 0.019$; no significant interaction between directionality bias group and trial block, $F(3.86, 177.47) = 1.954$, $p = 0.106$, $\eta_p^2 = 0.041$.

Figure 3

Bar graph displaying the results of Mixed ANOVA conducted on the absolute error rate of the accuracy check.

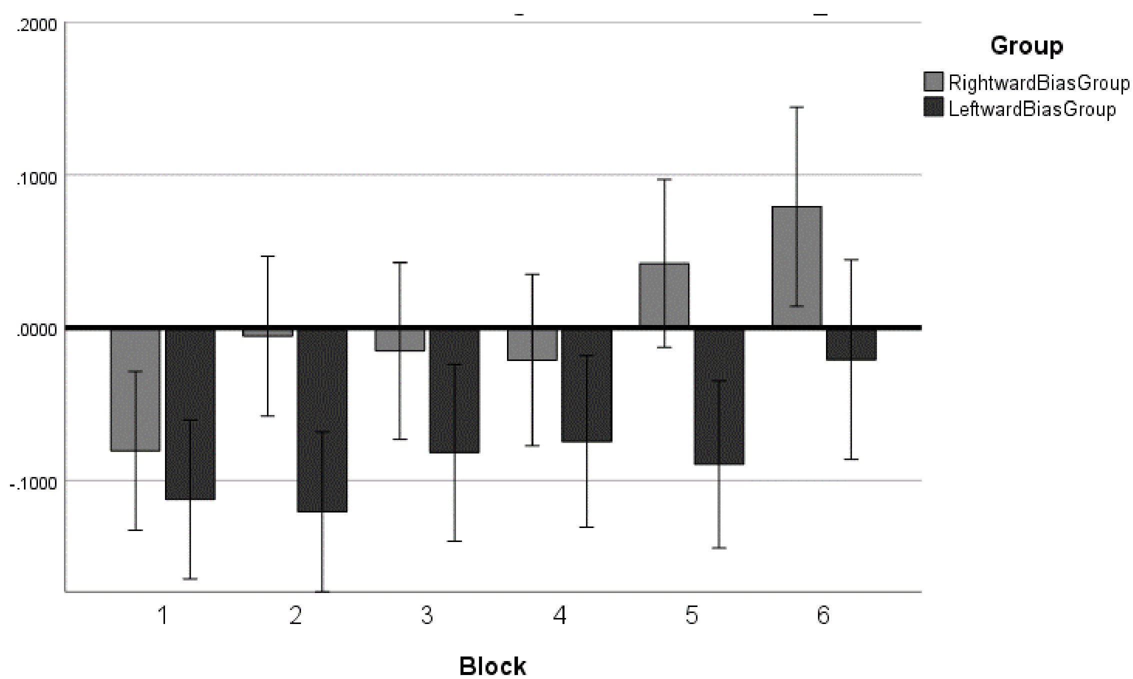


Note. Y-axis represents average absolute distance error in centimeters. Error bars represent standard error of the mean.

Furthermore, to ensure there were no accidental significant differences in the average displacement error between the groups or within the groups, a 2 (Directionality Bias Group: leftward or rightward) x 6 (Trial Block: block 1, block 2, block 3, block 4, block 5, & block 6) mixed analysis of variance (ANOVA) was conducted, with directionality bias as a between-subjects factor, and trial block group as a within-subject factors on each dependent variable. The results, displayed in Figure 4, indicated no significant main effect of directionality bias group on average displacement error, $F(1, 46) = 2.25$, $p = 0.140$, $\eta_p^2 = 0.047$; no significant main effect of trial block on average displacement error, $F(3.970, 182.626) = 1.782$, $p = 0.135$, $\eta_p^2 = 0.037$; no significant interaction between directionality bias group and trial block, $F(5, 230) = 0.372$, $p = 0.868$, $\eta_p^2 = 0.008$.

Figure 4

Bar graph displaying the results of Mixed ANOVA conducted on the average displacement error of the accuracy check.



Note. Y-axis represents distance of displacement error in centimeters. Error bars represent standard error of the mean.

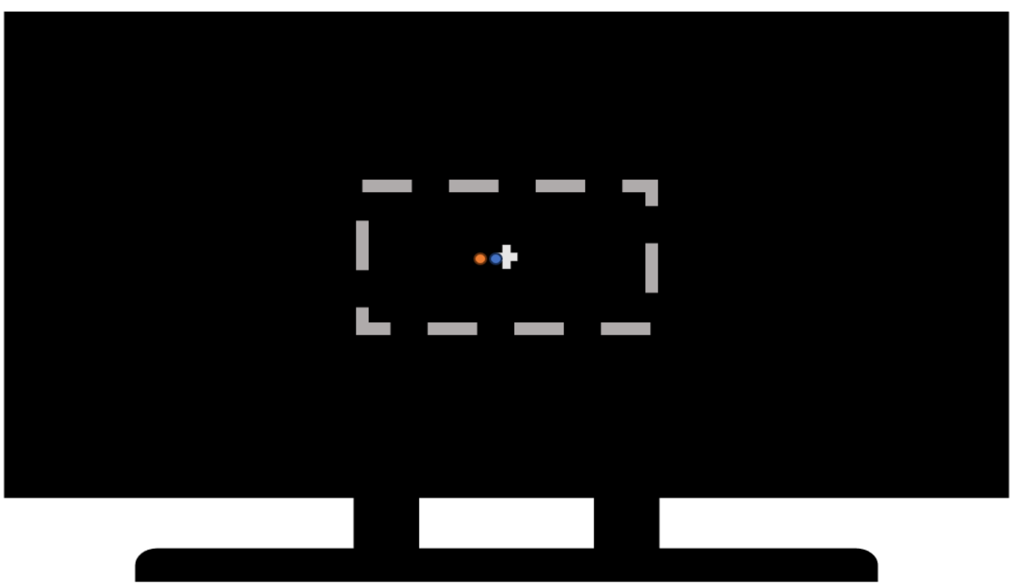
Potential Initial Unmanipulated Biases

Since I am interested in analyzing the influence of the directionality bias manipulation on participants' anticipatory fixation behaviour, I need to ensure two things. First, I need to ensure that any initial bias participants may have had for any reason other than the experimental manipulation is measured and considered. Second, I need to ensure there are no significant differences in terms of initial bias between the rightward and leftward bias groups that may have occurred by chance due to sampling errors.

To do so, I measured the fixation that was taking place prior to the appearance of the block, in the first two unmanipulated blocks of trials (Blocks 1 & 2). Since this fixation was not in response to any event taking place in the study, I can be confident that this fixation reflects any visual biases participants may have. The true center of the screen monitor, at which participants were starring is 26.350 cm. On average, I found that participants in the leftward bias group tended to fixate at 26.301 cm – about 0.049 cm to the left of the true center. Whereas participants in the rightward bias group tended to fixate at 25.998 cm, on average – about 0.303 cm to the left of the true center. Figure 5 shows the fixations of the leftward and rightward bias groups in relation to the true center of the screen monitor.

Figure 5

Figure representing the initial fixation position of each group.



Note. Cross represents the true center of the screen monitor. Blue dot represents the average for the leftward bias group fixation whereas the orange dot represents the average for the rightward bias group fixation. Target outline represents the location at which the target would eventually appear.

To ensure that there are no significant differences in terms of unmanipulated visual bias between the two groups, an independent samples t-test was conducted on the fixation that was taking place prior to the appearance of the block, in the first two blocks of trials, where no bias has yet been introduced. Results revealed that there is no significant effect of group, $t(46) = -0.828$, $p = 0.412$, despite the rightward bias group ($M = 25.998$, $SD = 1.38$) having a slight higher leftward bias than the leftward bias group ($M = 26.301$, $SD = 1.14$).

Fixations

Now that I have ensured that there are no significant differences in terms of visual bias between the groups, I can investigate the effects of the manipulation on the anticipatory fixation behaviour of participants. As mentioned earlier, I have identified five different fixations of interest, with each fixation occurring at a pre-defined time within the trial. Measurements for fixations were calculated as the distance *(in centimeters)* between the fixation and the center of mass of the target. A 2 (Directionality Bias Group: leftward or rightward) x 6 (Trial Block: block 1, block 2, block 3, block 4, block 5, & block 6) mixed analysis of variance (ANOVA) with directionality bias as a between-subjects factor, and trial block group as a within-subject factors on each of these five fixations.

Fixation 1 is defined as the first intentional fixation occurring after the appearance of the target. Results revealed no significant main effect of directionality bias group on Fixation 1, $F(1, 46) = 2.543$, $p = 0.118$, $\eta_p^2 = 0.052$; no significant main effect of trial block on Fixation 1, $F(3.293, 151.478) = 0.841$, $p = 0.482$, $\eta_p^2 = 0.018$; no significant interaction between directionality bias group and trial block, $F(3.293, 151.478) = 1.360$, $p = 0.256$, $\eta_p^2 = 0.029$. See Table 3 for mean scores of groups.

Fixation 2 is defined as the fixation containing the 1.00s timestamp. As the target begins moving at 2.50s, this fixation occurred while the target remained stationary. Results revealed no significant main effect of directionality bias group on Fixation 2, $F(1, 46) = 2.350$, $p = 0.132$, $\eta_p^2 = 0.049$; no significant main effect of trial block on Fixation 2, $F(3.487, 160.423) = 0.451$, $p = 0.746$, $\eta_p^2 = 0.010$; no significant interaction between directionality bias group and trial block, $F(3.487, 160.423) = 0.954$, $p = 0.426$, $\eta_p^2 = 0.020$. See Table 4 for mean scores of groups.

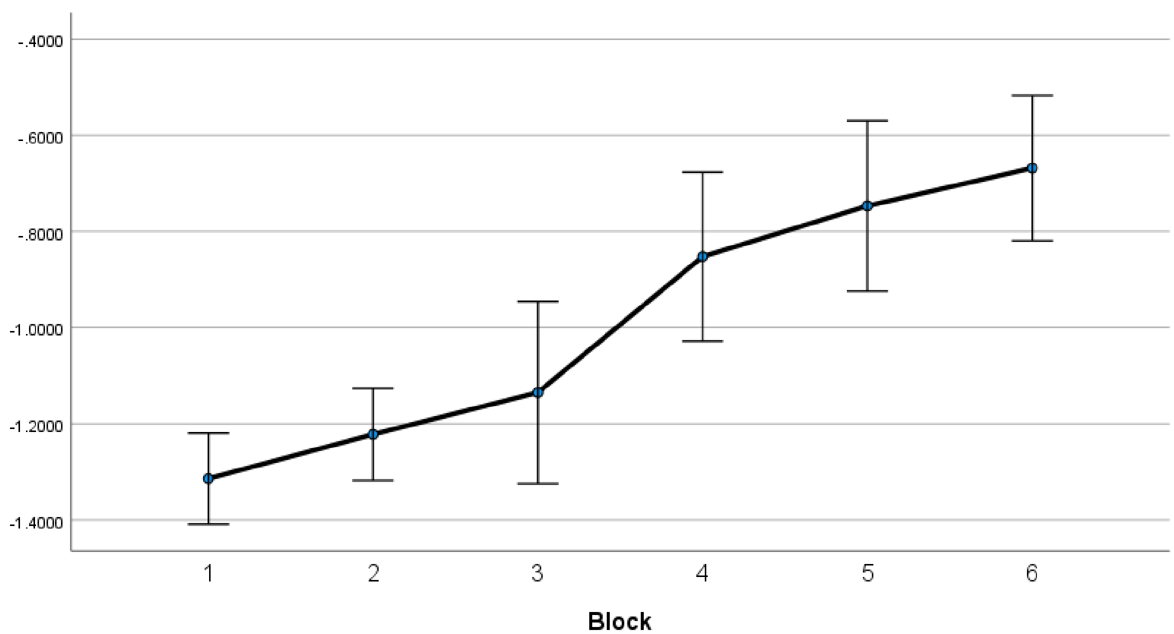
Fixation 3 is defined as the fixation containing the 2.00s timestamp. As the target begins moving at 2.50s, this fixation occurred while the target remained stationary. Results revealed no significant main effect of directionality bias group on Fixation 3, $F(1, 46) = 0.614$, $p = 0.437$, $\eta_p^2 = 0.013$; no significant main effect of trial block on Fixation 3, $F(3.042, 139.943) = 2.020$, $p = 0.113$, $\eta_p^2 = 0.042$; no significant interaction between directionality bias group and trial block, $F(3.042, 139.943) = 0.985$, $p = 0.402$, $\eta_p^2 = 0.021$. See Table 5 for mean scores of groups.

Fixation 4 is defined as the first intentional fixation following the onset of movement of the target. Results revealed no significant main effect of directionality bias group on Fixation 4, $F(1, 46) = 0.217$, $p = 0.644$, $\eta_p^2 = 0.005$. However, results revealed a significant main effect of trial block on Fixation 4, $F(3.306, 152.080) = 6.057$, $p< 0.001$, $\eta_p^2 = 0.116$. Post-hoc pairwise comparisons using the Bonferroni correction revealed that on average, Fixation 4 trailed the center of the target in Block 1 (M = -1.314, SD = 0.649) significantly more than it did in Block 5 (M = -0.747, SD = 1.217; $p = 0.017$) and Block 6 (M = -0.668, SD = 1.035; $p = 0.001$). Moreover, the post-hoc comparisons also revealed that Fixation 4 trailed the center of the target in Block 2 (M = -1.222, SD = 0.665) significantly more than it did in Block 6 (M = -0.668, SD =

1.035; $p = 0.014$). In other words, Fixation 4 was closer in distance to the center on the target in Block 5 and Block 6 than it was in Block 1. In addition, Fixation 4 was closer in distance to the center on the target in Block 6 than it was in Block 2. This means that as participants completed more trials, they tracked the target more closely, by following its center. Please see Table 6 for all post-hoc comparisons conducted. Results of the within-subject variable *(trial block)* are displayed in Figure 6. Finally, no significant interaction between directionality bias group and trial block were found, $F(3.306, 152.080) = 0.861$, $p = 0.472$, $\eta_p^2 = 0.018$. See Table 7 for mean scores of groups.

Figure 6

Line graph representing the effect of Trial Block on Fixation 4



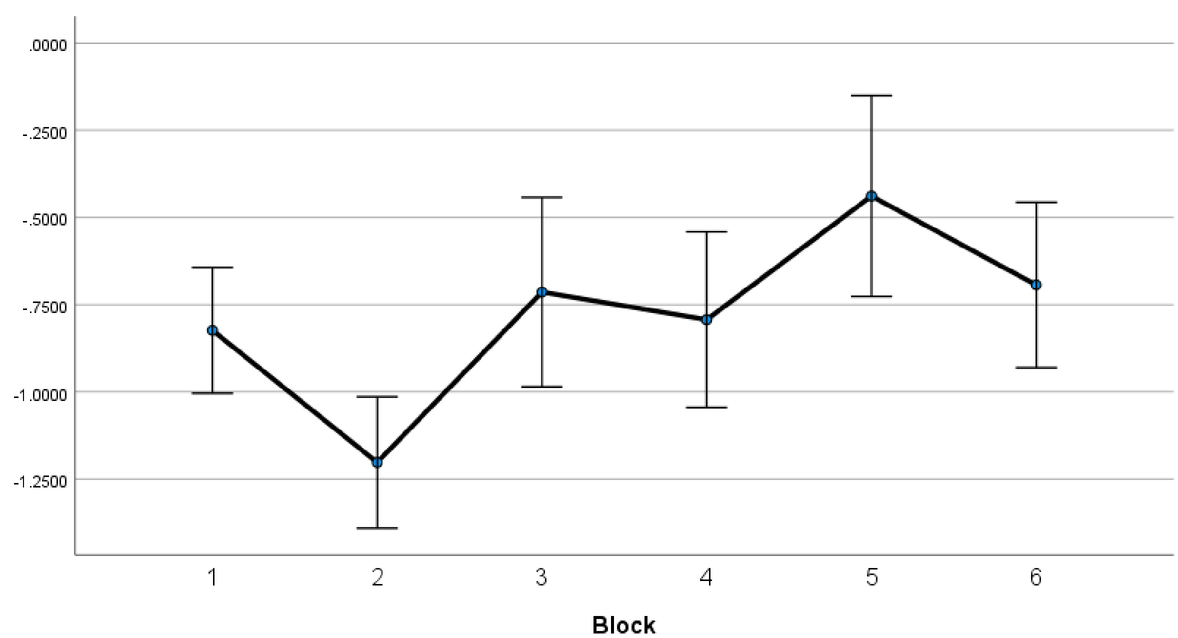
Note. Data represented in this graph is collapsed across the two between-subject groups, Rightward Bias Group & Leftward Bias Group. Y-axis represents distance from center of mass in centimeters. Error bars represent standard error of the mean.

Fixation 5 is defined as the first intentional fixation following the onset of the tone.

Results revealed no significant main effect of directionality bias group on Fixation 5, $F(1, 46) = 0.042$, $p = 0.839$, $\eta_p^2 = 0.001$. However, results revealed a significant main effect of trial block on Fixation 5, $F(3.195, 146.992) = 2.675$, $p = 0.046$, $\eta_p^2 = 0.055$. Post-hoc pairwise comparisons using the Bonferroni correction revealed that on average, Fixation 5 trailed the center of the target in Block 2 ($M = -1.202$, $SD = 1.290$) significantly more than it did in Block 5 ($M = -0.438$, $SD = 1.974$; $p = 0.031$). In other words, Fixation 5 was closer in distance to the center on the target in Block 5 than it was in Block 2. Please see Table 8 for all post-hoc comparisons conducted. Results of the within-subject variable *(trial block)* are displayed in Figure 7. Finally, no significant interaction between directionality bias group and trial block were found, $F(3.195, 146.992) = 0.260$, $p = 0.866$, $\eta_p^2 = 0.006$. See Table 9 for mean scores of groups.

Figure 7

Line graph representing the effect of Trial Block on Fixation 5



Note. Data represented in this graph is collapsed across the two between-subject groups, Rightward Bias Group & Leftward Bias Group. Y-axis represents distance from center of mass in centimeters. Error bars represent standard error of the mean.

Line Bisection Task

To measure the effect of the bias introduced during the visuomotor task on performance the line bisection test (LBT), a 2 (directionality bias group: leftward or rightward) x 2 (Test Timing: pre-test & post-test) Mixed Subjects ANOVA was conducted. The dependent variable for the LBT is the standardized deviation ratio for each of the 18 experimental lines, averaged out. The data showed that regardless of directionality bias group and test timing, participants on average, had a rightward bias, yielding a positive value for the average deviation ratio. This indicates that on average, participants perceived the center of the line to be more towards the right of the true center of the line; otherwise known as rightward bias. See Table 10 for the average deviation of each group.

Results of the mixed ANOVA revealed no significant main effect of directionality bias group on the average deviation value for the line bisection task, $F(1, 46) = 0.847$, $p = 0.362$, $\eta_p^2 = 0.018$; no significant main effect of test timing on the average deviation value for the LBT, $F(1, 46) = 2.411$, $p = 0.127$, $\eta_p^2 = 0.050$; no significant interaction between directionality bias direction and test timing, $F(1, 46) = 0.030$, $p = 0.863$, $\eta_p^2 = 0.001$. This implies that the manipulation introduced during the visuomotor task had no impact on performance in perceptual tasks, as evidenced by the absence of significant differences between the two between-subject variables (directionality bias group) and the within-subject variables (test timing).

CHAPTER IV

DISCUSSION

In this study, I sought to investigate the sensitivity of the human visual system to environmental statistics. To achieve this goal, I created a learning paradigm that involved the manipulation of the horizontal movement of a two-dimensional target, causing bias in the direction of the movement of the object. I asked participants to reach and grasp the target and explored their fixation behaviour during various distinct time points within a trial. Each trial consisted of the target appearing in the middle of the screen and moving horizontally either towards the right or the left, depending on the condition, stage within the learning paradigm, and type of trial. I was most interested in fixations that occurred prior to the onset of movement of the target, as these fixations would indicate anticipation of the direction of the movement (Land et al., 1999; Land, & Hayhoe, 2001). Moreover, I sought to explore the effects of the directionality bias introduced during the visuomotor task participants completed on their performance during perceptual tasks. Therefore, each participant completed two line-bisection tasks, once before partaking in the visuomotor learning paradigm, and once afterwards.

I identified five distinct timepoints during each trial as points of interest for deducing anticipation from participants' fixation behaviour. These five fixations are defined as follows: first intentional fixation after appearance of the target, fixation occurring during the 1.00 s timestamp, fixation occurring during the 2.00 s timestamp, first intentional fixation after onset of movement of target, and first intentional fixation after participants were directed to reach and grasp the target. For the line-bisection task, I measured the average deviation value to deduce any influence on spatial asymmetries that may have been caused by the directionality bias introduced during the visuomotor task.

Visuomotor Task – Anticipation Behaviour

Only three of the five fixations I have measured can truly be considered anticipatory behaviour. These fixations are Fixation 1, Fixation 2, and Fixation 3. These fixations are the only fixations considered anticipatory fixations because they occurred prior to the movement of the target, meaning that participants do not yet know in which direction the target will be moving. I did not find any significant differences between the rightward bias group and the leftward bias group. Additionally, I did not find any significant differences between blocks, which means that the anticipatory fixation behaviour did not change over time, suggesting that no learning had taken place.

My findings showed that the anticipatory fixation behaviour did not change over time, as participants completed more trials. In other words, I did not observe a significant difference between the behaviour for the three fixations (Fixation 1, Fixation 2, & Fixation 3) during the first two blocks of trials that did not contain any directionality bias, and the later four blocks of trials that contained extreme directionality bias towards one side. This suggests that the manipulation did not produce the hypothesized results, which stated that the human visual system would be sensitive to directionality bias and behave in a way that reveals the anticipation of the direction of the movement. More specifically, I hypothesized that participants would detect the direction of the bias I manipulated and fixate "ahead" of the center of the target in the direction of its anticipated movement, even in the absence of any indications regarding the direction of the movement of the target. My hypothesis was built on two factors: first, research shows that statistically regular events elicit anticipatory behaviour (Diaz et al., 2013; Hayhoe et al., 2012). Second, anticipatory behaviour is likely needed as it increases the chances of successfully completing the goal, which in this case, is grasping the target before it moves off the screen (Fiehler et al. 2019). In summary, I did not observe any signs that participants utilized the 75% - 25% directional bias to their advantage in terms of anticipation to increase their chances of successfully grasping the moving target. On the contrary, the behaviour I recorded suggests that participants stuck to a 50% - 50% strategy for their anticipatory fixation behaviour where fixations were mostly centered towards the middle of the target rather than towards either edge of the target. One can equate this strategy to the strategy of a tennis player who, after hitting the ball, runs back towards the middle of the pitch to increase their chances of hitting the ball again regardless of the side of the pitch towards which the opposing player will hit the ball. There are a few possible explanations for these results, and their lack of support for my hypotheses.

Fixation behaviour did not change as participants completed more trials, and was not influenced by the directionality bias. Previous studies have suggested that participants could pick a certain behaviour early on during a study, and maintaining that pattern of behaviour, regardless of the changes done to the manipulation of the variables in the experiment (Abbas et al., 2022). Therefore, in the light of these findings, I could interpret the lack of anticipatory fixation in the anticipated leading edge of the target because all participants were subjected to non-directionally biased trials prior to getting subjected to the directionality bias. This means that participants may have picked a successful strategy for fixations during the first two non-biased blocks, and stuck to that strategy for the rest of the study, regardless of the environmental statistics manipulations I included in my learning paradigm. This possibility could be tested by eliminating the first two blocks, and examining the fixation behaviour of participants if they were directly subjected to the directionality biased blocks, rather than completing the non-directionality bias blocks first.

Another possible explanation for the null results I received is the lack of reinforcement strategies built into my learning paradigm. In other words, I did not provide any rewards when participants successfully grasped the target before it moved off the screen, possibly disincentivizing participants from doing everything possible to successfully grasp the target. Previous research suggests that in lab studies, anticipatory oculomotor behaviour, could be viewed as an operant behaviour (Damasse et al., 2018; Fiehler et al. 2019). In a study conducted by Damasse and colleagues (2018), reward was found to have a significant effect on anticipatory smooth eye pursuit behaviour in the presence of directional bias. This suggests that the visuomotor system is sensitive to directional bias. However, further investigations are needed to understand the circumstances under which the visual system defaults to a center-driven behaviour, where 50% - 50% chance is assumed, and when the visual system becomes sensitive to environmental statistics.

Following up on the theme of the lack of necessity to anticipate the movement of the target, the relatively slow speed of the target may have eliminated the need for anticipating the direction of the movement in the target. This is because there was enough time for participants to perform a catch-up saccade and grasp the target between the target's onset movement and its movement off the screen. To be more specific, the time between the onset of movement of the target and the instance at which the leading edge of the target begins to disappear off the screen is 1753 msec (1.753 s). Previous research suggests that cognitive expectations produce anticipatory oculomotor behaviours (Kowler, 1989). Therefore, it is not unreasonable to conclude that if participants expected a possible challenge to their ability to grasp the target due to its high velocity, I may have observed anticipatory fixations.

Finally, the lack of anticipatory behaviour I observed could be a result of the degree of bias I utilized in this study. I utilized a 75%-25% directionality bias in my paradigm. It is possible that a larger directionality bias ratio would cause the visuomotor system to produce significant anticipatory behaviours. For instance, Kowler (1989) demonstrated the effect of certainty on anticipatory oculomotor behaviour. Participants were shown a tube that branches off into two arms at the bottom. Then, a ball was shown at the top of the tube and moved down the tube and into one of the two branches. It was found that participants performed stronger anticipatory oculomotor behaviour when they were cued about the direction of the movement of the ball. Cues included an auditory instruction or a visible barrier at the top of one of the branches of the tube (Kowler, 1989). Furthermore, previous studies in our lab that have observed anticipatory fixations in the direction of the eventual movement of the target have utilized a 100%-0% directionality bias, meaning that the target only moved towards one direction (Bulloch et al., 2015; Langridge & Marotta, 2020; Thulasiram et al., 2020). Thus, utilizing a larger directionality bias ratio in my visuomotor paradigm may serve as a stronger cue that elicits anticipatory fixation behaviour.

Although I did not see any meaningful difference between the six blocks of trials that participants completed, I did observe some meaningful results, in terms of anticipatory behaviour, from the between-group comparisons. I had two between-subject groups, a rightward bias group and a leftward bias group. I calculated fixations, not based on their location on the screen in relation to the world coordinate, but rather in relation to the center of the target. Therefore, fixations in the same location would have the same value, but a different sign, because for one condition, the fixation would be ahead of the center of the target in one condition and trailing the center of the target in the other condition. For more information on how the calculations were done, please see Figure 2. As mentioned earlier, previous work in our laboratory has shown that participants tend to fixate further ahead of the leading edge of a leftward moving target than they do for the leading edge of a rightward moving target (Bulloch et al., 2015). This behaviour likely occurs to overcome the mechanical constraint of grasping an object that is situated on one's left side with their right hand (Brenner & Smeets, 2007). In my current study, since I utilized opposite equations to calculate the fixation values for each group, the lack of statistical significance between them suggests that participants in both groups exhibited the same pattern of fixation behaviour, but in the opposite direction. This means that although I did not observe any differences in anticipatory fixations as participants completed more directionally-biased trials, the visual system was sensitive to directionality bias. This is evident by the lack of fixations that are to the left of the center of the target in both groups. Had the visual system not detected the directionality bias of the target, it is likely that participants in both groups would have fixated towards the left of the center of the target to compensate for the mechanical constraint of potentially performing a right-hand grasp of a leftward moving target (Carey et al., 1996). Therefore, these results suggest that compensating for this mechanical constraint is limited to instances where there is no ambiguity regarding the leftward movement of the target one wishes to manipulate with their right hand.

Visuomotor Task – Tracking Behaviour

Following the onset of movement of the target, I measured two fixations: the first intentional fixation after the target movement onset (Fixation 4), and the first intentional fixation after the presentation of the tone (Fixation 5). I hypothesized that upon the onset of target movement, participants would fixate towards the leading edge of the target. Given that these two fixations were performed after the target began moving, they do not give any insight into anticipatory behaviour, since participants are aware of movement direction at these time points. However, these fixations give insight into tracking behaviour, as well as the effects of practice on oculomotor behaviour.

For Fixation 4, results revealed that as participants completed more trials, their tracking behaviour of the target improved. I found a significant difference between Block 1 and Block 5 & Block 6, and a significant difference between Block 2 and Block 6. Previous research in our laboratory has revealed that once a target begins moving, participants tend to fixate on the leading edge of the target (Bulloch et al., 2015; Langridge & Marotta, 2020). However, that is not what I observed in this study. Results of this study revealed that at the beginning of the study, in Block 1, participants' fixations tended to trail the center of mass of the target. Furthermore, as participants completed more trials, the less their fixations trailed the center of the target. Having my results be incongruent with the behaviours that I have previously observed in previous studies is not surprising because this study is unique in the sense that participants were not cued about the expected movement direction of the target. For instance, in the study conducted by Bulloch and colleagues (2015), the target appeared either at the most rightward edge of the screen monitor and moved leftward or appeared at the most leftward edge of the screen and moved rightward. Whereas in my study, the target appeared in the middle of the screen, leaving the direction of its future movement ambiguous.

As mentioned earlier, my study did not show that participants performed any anticipatory fixations. These fixations are important as they provide behavioural advantages that increase one's chances of successfully executing the required goal-directed action (Mennie et al., 2007). Moreover, anticipating the direction of the movement of the target lessens the need for catch-up saccades following onset of movement of the target (de Brouwer et al., 2002). Previous research suggest that catch-up saccades are frequent when there are ambiguities about the direction of movement of the target (Boman & Hoston, 1992). Given the ambiguity of the direction of movement of the target in this study, it is not unreasonable to view Fixation 4 as the fixation following the catch-up saccade that participants performed to keep the target in their central vision. Thus, the location of the fixation is a result of the magnitude of the saccade.

The multiple process model of goal-directed aiming/reaching suggests that individuals reaching or aiming tend to undershoot the position of the target as undershooting the target is less costly to fix than overshooting the target (Elliott et al., 2001; Elliott et al., 2020). This indicates that the endpoint of the initial movement tends to be placed short of the center of the target. Elliott and colleagues (2020) termed this phenomenon as the "play-it-safe" strategy. The play-it-safe strategy is not exclusive to hand movements, but several studies have observed it in saccadic movements as well (Becker & Fuchs, 1969; Weber & Daroff, 1971). Moreover, this strategy was found to be reduced by practice leading to the reduction of undershooting, bringing the movement endpoint closer to the target (Elliott et al., 2004; Elliott et al., 2001). Therefore, it is not surprising that I observed that the distance between Fixation 4 and the midpoint of the target got narrower as participants completed more trials. At the beginning of the study, participants were undershooting the target to "play-it-safe" (Elliott et al., 2020), but as they completed more trials, the need for undershooting the target was reduced.

In addition to Fixation 4, I identified Fixation 5 as the second fixation of interest post target movement. As previously mentioned, Fixation 5 is the first intentional fixation after presentation of tone. Similarly, Fixation 5 can be thought of as the fixation occurring at the initiation of the reaching movement. Previous research suggests that this fixation occurs at the center of the target, for the horizontal axis (Bulloch et al., 2015). Moreover, this fixation was found to be closer to the final position of the index finger than the fixation of interest prior to it (Fixation 4). It was argued that Fixation 5 is closer to the final position of the index finger because it is a result of the online adjustment that occur after the initial saccade and fixation that occur after the onset of movement of the target (Bulloch et al., 2015). Therefore, as I viewed Fixation 4 as the end point of the catch-up saccade that occurred after the target has begun moving, I can view Fixation 5 as the end point of the online correction that occurred in preparation for grasping the target after the presentation of the tone.

In my study, the results of Fixation 5 revealed a significant within-subjects difference between Block 2 and Block 5. In all the six blocks of trials, Fixation 5 trailed the center of the target. However, in Block 2, this fixation trailed the center of the target the most (furthest away from center of target), whereas in Block 5, it trailed the center of the target the least (closest to center of target). Research shows that the online adjustment movements can vary, leading to different end points (Elliott et al., 2020). It is likely that these differences were caused by differences in the online adjustment movements that were not perfect early on during the visuomotor task, leading the endpoint (Fixation 5) to trail the center of the target, as observed in Block 2. Whereas, as participants completed more trials and got more practice, the online adjustment movements were improved, leading the endpoint (Fixation 5) to become closer to the center of the target, as observed in Block 5. If the visuomotor task included more trials blocks, it is likely that I would have observed Fixation 5 trailing the target less and less, as participants completed more trials.

I did not observe any significant results between the rightward bias group and the leftward bias group for Fixation 4 and Fixation 5. I calculated the position of Fixations 4 & 5 in relation to the target in the same way I did for Fixations 1, 2 & 3. Therefore, the sign of the fixation (positive or negative; ahead center of target or trailing it) depends on which condition the trial is in. The lack of significance observed between the two groups for Fixations 4 & 5 suggests that direction does not affect the fixation behaviour involved in reaching and grasping.

This finding is contradictory to the previous findings that suggest individuals may have a leftward bias either due to overcoming the mechanical constraint of grasping a leftward translating target with one's right hand (Brenner & Smeets, 2007) or due to the previously discussed phenomenon known as pseudoneglect (de Bruin et al., 2014). If participants had a leftward bias for either reason, I should have observed a significant difference between the leftward bias group and the rightward bias group.

Pseudoneglect

A secondary purpose of this study was to investigate the effects of directionality bias established during the visuomotor task on perceptual task performance. To achieve this goal, participants completed the same perceptual task twice, once before the visuomotor task (to obtain a baseline of performance), and once after the visuomotor task (to examine the effects of the directional bias on perception). The perceptual task I utilized for this study is the line-bisection task. There are several versions of the line-bisection task, but I replicated the task utilized by Schenkenberg and colleagues (1980). Although this task requires a motor response (marking the perceived midpoint of each line using a pencil), previous research suggests that this test is a valid task to measure perceptual judgement (Haffenden & Goodale, 1998). To achieve the secondary goal of this study, I compared the pre-test and post-test line bisection tasks of the two groups, the leftward bias group and the rightward bias group. Furthermore, I compared the pre-test and post-test within each group.

Results of the pre-test line bisection tasks revealed no significant difference between the two groups, the rightward and leftward bias groups. Regardless of group, participants displayed a rightward bias. This means that on average, participants perceived the center of the line to be on the right of the true center of the line. These findings partially support my hypothesis. I had initially hypothesized that there would be no significant difference in pre-test line bisection task performance between the two groups. This hypothesis was based on the fact that participants were randomly recruited from the participants subject pool and were randomly assigned to either group. This hypothesis was supported by the results. However, I also hypothesized that participants would display pseudoneglect, meaning they would display leftward bias. However, that hypothesis was not supported. Observing rightward bias yields some potentially insightful support for the interhemispheric competition theory of visual attention.

Observing a rightward bias on line bisection tasks is not uncommon. For instance, Manning and colleagues (1990) conducted a study to investigate pseudoneglect and discovered that 50% of their sample exhibited a rightward bias, whereas the other 50% exhibited a leftward bias. Moreover, research suggests that pseudoneglect is not reliable across different tests (Learmonth et al., 2015) and different modalities (Brooks et al., 2016). The results of the current study highlight a significant shortcoming of the hemispheric asymmetry theory of visual attention which suggests that the leftward bias (pseudoneglect) individuals exhibit during the completion of perceptual tasks is a result of the dominance of the right hemisphere which leads to bias towards the contralateral visual field – the left visual field (Thiebaut et al., 2011). However, my results support the interhemispheric competition theory of visual attention. This theory posits that both the rightward and leftward hemispheres inhibit each other, leading visual bias to be produced because of the sum of the activation of both hemispheres (Cohen et al., 1994; Szczepanski et al., 2010; Szczepanski & Kastner, 2013). I cannot claim that this conclusively concludes the debate regarding the neural underpinnings of visual attention. As mentioned earlier, this debate is very complex as many studies produce results that could be interpreted differently, to support either theory (Wang et al., 2023). Moreover, previous research suggests that the different versions of the same perceptual task could produce different results. For instance, research has shown that aspects of the line bisection task, such as line length, line elevation, line aspect ratio, and azimuthal line position could influence the direction of visual asymmetry that participants exhibit while completing the line bisection task (McCourt & Jewell, 1999). In conclusion, my study adds to a wide range of competing findings that support interhemispheric competition theory, but more research is needed for one theory of visual attention to be conclusively supported.

For the line bisection task, I hypothesized that performance between the pre-test line bisection task and the post-test line bisection task would be significantly different. However, my results revealed no significant differences between the pre-test and post-test line bisection tasks. In other words, regardless of which group participants were in, all participants exhibited the same level of visual bias in the pre-visuomotor-task line bisection task and the post-visuomotor-task line bisection task. This means that the directionality bias introduced during the visuomotor task did not influence the vision-for-perception system (the line bisection task). That is not surprising since I did not observe any clear effects of directionality bias on perception when action is required. More specifically, since I did not observe any effects of directionality bias on anticipatory fixations, it is not surprising that I did not see any effects of it on visual attention on perceptual tasks. Ultimately, regardless of the direction of directionality bias (rightward or leftward), it had no effect on visual perception when action is not required.

Indeed, even if I observed a significant effect of directionality bias on anticipatory behaviour (or visual perception when action is required, more generally), that effect may have not transferred to the line bisection task due to potential flaw in my methodology. Previous studies have revealed that the level of visual bias unveiled by perceptual task could be different depending on whether the task was presented in the superior or inferior visual fields (McCourt & Jewell, 1999). More specifically, it was found that pseudoneglect was most significant when the line bisection task was presented in the superior visual field (McCourt & Jewell, 1999). In my study, both the line bisection task and the target appeared in the inferior visual field. However, the line bisection task was presented to participants on the table, whereas the target appeared on the monitor in front of the participants, but remained in the inferior visual field. The discrepancy in the position of the presentation of the target & the line bisection task, even though both were presented in the inferior visual field, may have affected the transfer of the effects of directionality bias from the visuomotor task on the line bisection task. Moreover, research suggests that completing perceptual tasks in near versus far space recruits the activation of different neural networks (Weiss et al., 2000). More specifically, completing perceptual tasks in the near space activates dorsal visuomotor processing areas. However, completing perceptual tasks in the far space activates ventral visuoperceptual processing areas (Weiss et al., 2000). Therefore, to avoid possible confounds of positional presentation of task or proximity of the task to the participant, future research investigating the same research question should present all stimuli on the same monitor.

Implications and Future Directions

Several studies have demonstrated that environmental statistics are utilized to predict future events (Kok et al., 2017; Notaro et al., 2019). These predictions lead to the production of anticipatory behaviour which in turn, increases the chances of one's success at successfully completing a certain goal-directed behaviour (Bulloch et al., 2015, Mennie et al., 2007; Thulasiram et al., 2020). My results revealed that the visual system was not sensitive to environmental statistics, and therefore, did not produce any anticipatory behaviour to increase one's chances of successfully completing a goal-directing action. This finding suggests that the phenomena of how, or perhaps when, the visual system can detect and utilize environmental statistics is not fully understood. Future work in this area should focus on identifying the conditions under which environmental statistics are detected. For instance, are factors relating to the difficulty of the goal-directed action being completed lead to increase sensitivity to environmental statistics? Or is there a minimum level of cuing needed for the visual system to detect environmental statistics?

In conditions where research has revealed that the visual system is influenced by environmental statistics, what is the likelihood that this influence would be generalized to other tasks where action may not necessarily be required? Several studies have investigated the correlation between visual bias exhibited during the completion of perceptual tasks and other tasks, such as free visual exploration tasks (Chiffi et al., 2021). In my study, the visual system did not produce anticipatory behaviour. In addition, there was no transfer of influence from directionality bias from the visuomotor task on to the perceptual task. Thus, future research should investigate the generalizability of visual asymmetry that may be influenced by environmental statistics of a target one wishes to act upon, on to other immediate situations that may not require action. Furthermore, research shows that visual asymmetry may be revealed by an individual's oculomotor behaviour, in addition to their results of perceptual tasks (Nuthmann & Clark, 2023). Thus, it is important that factors, other than perceptual tasks, are investigated to gain further insight regarding visual asymmetry that may not be detected by perceptual tasks.

This research has real world implications as it advances our understanding of the visuomotor system since it explores the integration between the perception and action elements of goal-directed behaviour. I maintain my stance that behavioural investigations must be utilized first to explore the intricacies of visual attention and visual asymmetry. Only after understanding the behaviour itself, I could utilize technologically advanced neuroimaging techniques that could determine the neural substrates of these complex behaviours (Krakauer et al., 2017).

Increasing our understanding of the organization and functions of the visuomotor system will lead to the enhancement of rehabilitation techniques for people who lost their visuomotor abilities due to brain damage, as it would allow for the creation of dual-task rehabilitation training, combining motor and visual training, rather than employing separate rehab training for the motor and visual aspects of goal-directed behaviours. Previous research has revealed that dual-task rehabilitation training is more effective at restoring function following a stroke than single-task rehabilitation training (Kim et al., 2014). Furthermore, this understanding will allow for the advancement in the of fields of robotics and artificial intelligence (AI). One of the biggest challenges in these fields is creating systems that can collect and process sensory information as efficiently and effortlessly as humans do (Lukic et al., 2014). Therefore, advancing this research is one of the pillars of advancing AI and robotics research as it provides the guidelines for efficiently creating AI technology capable of functioning with human-like skills. Moreover, by understanding how the brain is organized to process and integrate information, I can create intelligent machines that have implications for areas where the movement of an object must be predicted "on the fly" in novel scenes, such as missile interception systems for the military.

General Conclusions

In conclusion, this study reveals that the sensitivity of the visual system to environmental statistics is not constant, but dependent on need. I propose the potential existence of a minimum threshold for cuing for the pattern of directional bias that must be met for it to be detected by the visual system. Further research is needed to investigate the existence and magnitude of this threshold. Furthermore, my study did not show significant generalizability of visual asymmetry that is manipulated by directionality bias to visual asymmetry levels revealed by perceptual tasks that do not require action. This is not to say that this generalizability cannot occur. I conclude that under the conditions of the study, visual asymmetry may not generalize because anticipatory behaviour was not observed. Further research is required to examine the conditions under which visual asymmetry that is manipulated by directionality bias is generalized to other immediate situations where action is not required. Regarding the neural underpinnings of pseudoneglect, my findings support the interhemispheric competition theory of visual attention. Investigating the behavioural correlates of the neural organization of the visual system, and the neural networks implicated with it, has many benefits in the fields of rehabilitation, artificial intelligence, as well as military and spaceflight.

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Appendix A

Modified Edinburgh Handedness Assessment

Sex assigned at birth: ______ Participant ID: ___________

Age: ________ Ocular Dominance: _____________

Native Reading Language: _____________

Do You have normal or corrected to normal vision? ____________________________________

Handedness Inventory: Which hand do you use to do the following? Circle L or R

1. Throw a ball. L / R
2. Brush your teeth. L / R
3. Eat soup with a spoon. L / R
4. Comb your hair. L / R
5. Cut bread with a knife. L / R
6. Swing tennis/badminton racquet or bat. L / R
7. Hammer a nail. L / R
8. Point to something accurately. L / R
9. Write your name. L / R

Is there anything you do consistently with your left hand? _______________________________

Appendix B

Figure is not to scale.

Appendix C

Table 1

Mean Values for Fixation Measurement Accuracy: Absolute Error Rate

	Group	Mean	Std. Deviation	N
Block 1	Rightward Bias Group	.29	.14	24
	Leftward Bias Group	.30	.13	24
	Total	.30	.13	48
Block 2	Rightward Bias Group	.28	.13	24
	Leftward Bias Group	.30	.13	24
	Total	.29	.13	48
Block 3	Rightward Bias Group	.36	.20	24
	Leftward Bias Group	.31	.14	24
	Total	.34	.18	48
Block 4	Rightward Bias Group	.31	.14	24
	Leftward Bias Group	.32	.13	24
	Total	.31	.13	48
Block 5	Rightward Bias Group	.29	.12	24
	Leftward Bias Group	.34	.13	24
	Total	.31	.13	48
Block 6	Rightward Bias Group	.33	.13	24
	Leftward Bias Group	.25	.10	24
	Total	.29	.13	48

Note. All values are displayed in centimetres (cm).

Table 2

Mean Values for Fixation Measurement Accuracy: Average Displacement Error

	Group	Mean	Std. Deviation	N
Block 1	Rightward Bias Group	-.08	.23	24
	Leftward Bias Group	-.11	.27	24
	Total	-.10	.25	48
Block 2	Rightward Bias Group	-.01	.24	24
	Leftward Bias Group	-.12	.27	24
	Total	-.06	.26	48
Block 3	Rightward Bias Group	-.02	.31	24
	Leftward Bias Group	-.08	.26	24
	Total	-.05	.28	48
Block 4	Rightward Bias Group	-.02	.25	24
	Leftward Bias Group	-.07	.29	24
	Total	-.05	.27	48
Block 5	Rightward Bias Group	.04	.25	24
	Leftward Bias Group	-.09	.29	24
	Total	-.02	.27	48
Block 6	Rightward Bias Group	.08	.34	24
	Leftward Bias Group	-.02	.30	24
	Total	.03	.32	48

Note. All values displayed in centimetres (cm).

Appendix D

Table 3

Average fixation values for Fixation 1

	Group	Mean	Std. Deviation	N
Block 1	Rightward Bias Group	.13	.61	24
	Leftward Bias Group	.05	.37	24
	Total	.09	.50	48
Block 2	Rightward Bias Group	.04	.57	24
	Leftward Bias Group	.00	.62	24
	Total	.02	.59	48
Block 3	Rightward Bias Group	-.34	1.30	24
	Leftward Bias Group	.22	.88	24
	Total	-.06	1.13	48
Block 4	Rightward Bias Group	-.12	1.09	24
	Leftward Bias Group	.52	1.83	24
	Total	.20	1.53	48
Block 5	Rightward Bias Group	-.17	1.16	24
	Leftward Bias Group	.44	1.48	24
	Total	.13	1.35	48
Block 6	Rightward Bias Group	.18	1.33	24
	Leftward Bias Group	.43	1.36	24
	Total	.30	1.34	48

Note. All values displayed in centimetres (cm). Positive values indicate that fixation is ahead of center of mass of target. Negative values indicate that fixation is trailing the center of mass of target.

Table 4

Average fixation values for Fixation 2

	Group	Mean	Std. Deviation	N
Block 1	Rightward Bias Group	-.01	.36	24
	Leftward Bias Group	.07	.44	24
	Total	.03	.40	48
Block 2	Rightward Bias Group	.11	.38	24
	Leftward Bias Group	.04	.41	24
	Total	.07	.40	48
Block 3	Rightward Bias Group	-.24	1.00	24
	Leftward Bias Group	.23	1.22	24
	Total	.00	1.13	48
Block 4	Rightward Bias Group	-.15	.78	24
	Leftward Bias Group	.36	1.71	24
	Total	.10	1.34	48
Block 5	Rightward Bias Group	-.18	1.03	24
	Leftward Bias Group	.21	1.09	24
	Total	.02	1.07	48
Block 6	Rightward Bias Group	.07	1.35	24
	Leftward Bias Group	.37	.91	24
	Total	.22	1.15	48

Note. All values displayed in centimetres (cm). Positive values indicate that fixation is ahead of center of mass of target. Negative values indicate that fixation is trailing the center of mass of target.

Table 5

Average fixation values for Fixation 3

	Group	Mean	Std. Deviation	N
Block 1	Rightward Bias Group	.01	.36	24
	Leftward Bias Group	-.03	.36	24
	Total	-.01	.36	48
Block 2	Rightward Bias Group	.13	.47	24
	Leftward Bias Group	.13	.34	24
	Total	.13	.40	48
Block 3	Rightward Bias Group	-.04	1.12	24
	Leftward Bias Group	.04	.68	24
	Total	.00	.92	48
Block 4	Rightward Bias Group	.31	1.04	24
	Leftward Bias Group	.35	1.36	24
	Total	.33	1.20	48
Block 5	Rightward Bias Group	-.16	1.27	24
	Leftward Bias Group	.44	1.56	24
	Total	.14	1.44	48
Block 6	Rightward Bias Group	.32	1.10	24
	Leftward Bias Group	.47	.74	24
	Total	.39	.93	48

Note. All values displayed in centimetres (cm). Positive values indicate that fixation is ahead of center of mass of target. Negative values indicate that fixation is trailing the center of mass of target.

Table 6

Pairwise comparisons for the within-subject variable (Trial Block) for Fixation 4

(I) Block	(J) Block	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
Block 1	Block 2	-.09	.10	1.000	-.40	.21
	Block 3	-.18	.19	1.000	-.78	.42
	Block 4	-.46	.17	.120	-.98	.05
	Block 5	-.57*	.16	.017	-1.07	-.06
	Block 6	-.65*	.15	.001	-1.11	-.19
Block 2	Block 1	.09	.10	1.000	-.21	.40
	Block 3	-.09	.19	1.000	-.67	.50
	Block 4	-.37	.17	.529	-.90	.16
	Block 5	-.48	.18	.163	-1.03	.08
	Block 6	-.55*	.16	.014	-1.04	-.07
Block 3	Block 1	.18	.19	1.000	-.42	.78
	Block 2	.09	.19	1.000	-.50	.67
	Block 4	-.28	.13	.507	-.68	.12
	Block 5	-.39	.15	.165	-.84	.07
	Block 6	-.47	.16	.084	-.96	.03
Block 4	Block 1	.46	.17	.120	-.05	.98
	Block 2	.37	.17	.529	-.16	.90
	Block 3	.28	.13	.507	-.12	.68
	Block 5	-.11	.13	1.000	-.51	.30
	Block 6	-.18	.12	1.000	-.56	.19
Block 5	Block 1	.57*	.16	.017	.06	1.07
	Block 2	.48	.18	.163	-.08	1.03
	Block 3	.39	.15	.165	-.07	.84
	Block 4	.11	.13	1.000	-.30	.51
	Block 6	-.08	.13	1.000	-.48	.32
Block 6	Block 1	.65*	.15	.001	.19	1.11
	Block 2	.55*	.16	.014	.07	1.04
	Block 3	.47	.16	.084	-.03	.96
	Block 4	.18	.12	1.000	-.19	.56
	Block 5	.08	.13	1.000	-.32	.48

Note. Mean Difference values are displayed in centimeters. * represents significant mean differences at $p < 0.05$. All pairwise comparisons were conducted using the Bonferroni correction.

Table 7

Average fixation values for Fixation 4

	Group	Mean	Std. Deviation	N
Block 1	Rightward Bias Group	-1.34	.76	24
	Leftward Bias Group	-1.28	.53	24
	Total	-1.31	.65	48
Block 2	Rightward Bias Group	-1.12	.69	24
	Leftward Bias Group	-1.33	.63	24
	Total	-1.22	.67	48
Block 3	Rightward Bias Group	-1.14	1.36	24
	Leftward Bias Group	-1.13	1.27	24
	Total	-1.13	1.30	48
Block 4	Rightward Bias Group	-.62	1.24	24
	Leftward Bias Group	-1.09	1.19	24
	Total	-.85	1.23	48
Block 5	Rightward Bias Group	-.72	1.32	24
	Leftward Bias Group	-.78	1.14	24
	Total	-.75	1.22	48
Block 6	Rightward Bias Group	-.68	1.07	24
	Leftward Bias Group	-.66	1.02	24
	Total	-.67	1.04	48

Note. All values displayed in centimetres (cm). Positive values indicate that fixation is ahead of center of mass of target. Negative values indicate that fixation is trailing the center of mass of target.

Table 8

Pairwise comparisons for the within-subject variable (Trial Block) for Fixation 5

					95% Confidence Interval for Difference[b]	
(I) Block	(J) Block	Mean Difference (I-J)	Std. Error	Sig.[b]	Lower Bound	Upper Bound
Block 1	Block 2	.38	.14	.130	-.05	.81
	Block 3	-.11	.26	1.000	-.90	.68
	Block 4	-.03	.27	1.000	-.86	.80
	Block 5	-.38	.26	1.000	-1.19	.42
	Block 6	-.13	.24	1.000	-.86	.60
Block 2	Block 1	-.38	.14	.130	-.81	.05
	Block 3	-.49	.23	.605	-1.21	.23
	Block 4	-.41	.23	1.000	-1.13	.31
	Block 5	-.76*	.23	.031	-1.49	-.04
	Block 6	-.51	.21	.304	-1.16	.15
Block 3	Block 1	.11	.26	1.000	-.68	.90
	Block 2	.49	.23	.605	-.23	1.21
	Block 4	.08	.17	1.000	-.43	.59
	Block 5	-.28	.21	1.000	-.92	.37
	Block 6	-.02	.20	1.000	-.65	.61
Block 4	Block 1	.03	.27	1.000	-.80	.86
	Block 2	.41	.23	1.000	-.31	1.13
	Block 3	-.08	.17	1.000	-.59	.43
	Block 5	-.35	.18	.907	-.92	.22
	Block 6	-.10	.16	1.000	-.61	.41
Block 5	Block 1	.38	.26	1.000	-.42	1.19
	Block 2	.76*	.23	.031	.04	1.49
	Block 3	.28	.21	1.000	-.37	.92
	Block 4	.35	.18	.907	-.22	.92
	Block 6	.25	.18	1.000	-.31	.82
Block 6	Block 1	.13	.24	1.000	-.60	.86
	Block 2	.51	.21	.304	-.15	1.16
	Block 3	.02	.20	1.000	-.61	.65
	Block 4	.10	.16	1.000	-.41	.61
	Block 5	-.25	.18	1.000	-.82	.31

Note. Mean Difference values are displayed in centimeters. * represents significant mean differences at $p < 0.05$. All pairwise comparisons were conducted using the Bonferroni correction.

Table 9

Average fixation values for Fixation 5

	Group	Mean	Std. Deviation	N
Block 1	Rightward Bias Group	-.91	1.35	24
	Leftward Bias Group	-.74	1.14	24
	Total	-.82	1.24	48
Block 2	Rightward Bias Group	-1.20	1.29	24
	Leftward Bias Group	-1.20	1.32	24
	Total	-1.20	1.29	48
Block 3	Rightward Bias Group	-.77	1.42	24
	Leftward Bias Group	-.65	2.25	24
	Total	-.71	1.86	48
Block 4	Rightward Bias Group	-.91	.96	24
	Leftward Bias Group	-.67	2.27	24
	Total	-.79	1.73	48
Block 5	Rightward Bias Group	-.51	1.77	24
	Leftward Bias Group	-.36	2.19	24
	Total	-.44	1.97	48
Block 6	Rightward Bias Group	-.60	1.42	24
	Leftward Bias Group	-.79	1.83	24
	Total	-.69	1.63	48

Note. All values displayed in centimetres (cm). Positive values indicate that fixation is ahead of center of mass of target. Negative values indicate that fixation is trailing the center of mass of target.

Appendix E

Table 10

Average deviation for Line Bisection Task

	Group	Mean	Std. Deviation	N
Pre-test	Rightward Bias Group	1.05	1.40	24
	Leftward Bias Group	1.48	1.45	24
	Total	1.27	1.43	48
Post-test	Rightward Bias Group	.83	1.74	24
	Leftward Bias Group	1.20	1.81	24
	Total	1.01	1.77	48

Note. Positive values indicate rightward bias (bias to the right of the true center of the line), whereas negative values indicate leftward bias (bias to the left of the true center of the line).