Reduced global processing bias in people with a history of mild traumatic brain injury: Grass everywhere and not a field in sight

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Abstract

Mild traumatic brain injury (mTBI) is increasingly recognized as a disconnection syndrome, due to the prevalence of disrupted long-range connections. Long-range connections refer to neural pathways that span across brain regions, allowing communication and synchronization between different brain areas. Disruption of these connections is associated with the inability to efficiently integrate local information (i.e., multiple visual attributes) into the percept of a single global shape. The aim of this thesis was to investigate whether people with a history of mTBI exhibit a reduced ability to integrate local information into meaningful context.

Chapter 2 investigated whether visual integration was impaired in people with a history of mTBI, using visual illusions. Susceptibility to visual illusions demonstrates effective integration of visual information to provide a global picture, with surrounding elements automatically integrated into the perception of local elements. Results from Chapter 2 revealed that people with a history of mTBI exhibited decreased susceptibility to visual illusions, suggesting diminished automatic integration of visual information in a global manner; rather, these individuals appeared to prioritize analysis of local details within a visual stimulus. To further investigate this assumption, we employed the Navon task in Chapter 3 to assess whether people with a history of mTBI demonstrated a tendency to prioritize the processing of local details over global information when presented with multiple objects. This task was chosen as it provides a reliable measure of the extent to which individuals engage in global or local processing. The results revealed that people with a recent history of mTBI (within 12 months) had a reduced bias towards processing global elements of a figure (i.e., attending to the overall configuration of the object), indicating a reduced automatic tendency to process visual information as a coherent global percept. In contrast, individuals who sustained their most recent mTBI more than one year earlier displayed the same global processing bias as control participants (i.e., they attended to the overall structure of the visual stimulus first).

Following this observation, it was speculated that people with a history of mTBI may also apply a de-automatized processing style to their movements. It has been argued that individuals with a high propensity to consciously process their movements are more likely to display de-automaticity (inefficient or disrupted movement); therefore, in Chapter 4 we

assessed the propensity of people with a history of mTBI to consciously monitor and control their movements, using the Movement Specific Reinvestment Scale (MSRS). The results showed that people with a history of mTBI had a higher propensity for MSRS than controls. In addition, we found that time since most recent mTBI was negatively associated with the conscious motor processing subscale of the MSRS.

Chapter 5 builds upon the findings presented in Chapters 2 and 3, delving into the potential implications for real-world behaviours like visual anticipation. Specifically, this chapter investigated the impact of mTBI on individuals' ability to anticipate both deceptive and non-deceptive movements. The results demonstrate that people with a history of mTBI display significantly better anticipation of both deceptive and non-deceptive movements compared to control. Additionally, it was observed that people with a history of mTBI took longer to respond compared to controls.

The findings of this thesis suggest that there is an increased tendency to deconstruct visual and movement information following mTBI, highlighting a need for further research to better understand the effects of mTBI on information processing and to develop effective diagnostic and treatment strategies.[1]

[1] For the first two years of my candidacy, I was forced to study remotely because Covid-19 restrictions prevented entry to I spent the first two years of my New Zealand. Consequently, only the final year of study (from July 2022) was completed in-person at the University of Waikato.

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Sidhu, A., Uiga, L., Langley, B., & Masters, R.S.W. (under review). Anticipation of deceptive and non-deceptive movements in club rugby players with a history of mild traumatic brain injury. *The Journal of Sport and Exercise Science*

Conference presentations

Sidhu, A., Uiga, L., Langley, B., & Masters, R.S.W. (2022, December). The use of a first-person shooting game to assess cognitive function in mTBI. Australasian Skill Acquisition Network conference, La Trobe University, Melbourne, Australia.

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Chapter 1
General introduction

Mild traumatic brain injury (mTBI) is a prevalent condition, affecting approximately 42 million individuals annually (Gardner & Yaffe, 2015), and is also recognized as a leading cause of disability worldwide (Delouche et al., 2016). Despite the significant impact of mTBI, very little is known about the impaired integration of sensory processing that underlies the reported deficits in people with mTBI (Alwis, Johnstone, & Rajan, 2013).

mTBI is associated with a range of cognitive, emotional, and perceptual difficulties. These deficits, although diverse in nature, all require the coordination and integration of information across various regions of the brain. With mTBI being widely acknowledged as a disorder of brain connectivity (Hayes et al., 2016), it is reasonable to assume that mTBI-related disruptions in neural structure and function may hinder the ability to effectively integrate information across brain regions (Konigs et al., 2015).

The visual system is particularly vulnerable to mTBI, due to the delicate nature of its neural networks, making perceptual organization, a process that integrates and coordinates information, particularly susceptible to diffuse integration impairments following mTBI. Perceptual organization refers to the process of organizing visual information into coherent units, such as objects or patterns (Pomerantz, 1981). Gestalt psychologists argue that perceptual organization is achieved by a set of grouping principles (Coren & Girgus, 1980). These principles specify how image features, such as proximity, continuity, and similarity, can modulate how perceptual elements are grouped together in a visual scene to form a meaningful structure.

The ability to perceive objects as whole entities rather than individual elements refers to global processing. Global processing is crucial for tasks, such as face recognition, scene perception, and understanding complex visual stimuli. Healthy people generally demonstate a cognitive bias towards the processing of global information (i.e., global processing bias), prioritizing the perception of the "whole" before attending to its constituent parts (Kimchi, 1992, Navon, 1977).

Conversely, the ability to process information at the local or global level, can be impaired following brain damage (Delis, Robertson, & Efron, 1986; Lux et al., 2006; Robertson & Lamb, 1991). Indeed, much research has accumulated to show that abnormal local or global processing biases can disrupt the processing of visual stimuli, which may, in turn, result in challenges in daily adaptive behaviors like social interactions, anticipation or perceptual-motor coordination (Campanella & Belin, 2007; Lalanne & Lorenceau, 2004).

1.1 Pathophysiology of mTBI

1.1.1 Neuroanatomy: Anatomy of the brain

The nervous system is composed of the central nervous system (CNS) and the peripheral nervous system (PNS). The CNS consists of the brain and spinal cord. The PNS, on the other hand, comprises a group of neurons called ganglia and peripheral nerves that extend beyond the CNS, facilitating communication between the CNS and the rest of the body (Du et al., 2017). Neurons are specialized cells that have a unique structure, consisting of a cell body, dendrites, and an axon (Zhang, 2019). The cell body contains the nucleus and other organelles necessary for the neuron's functioning. Dendrites are specialized extensions of the cell body and are responsible for receiving synaptic inputs from other neurons and transmitting these signals to the cell body (Fiala & Harris, 1999). In contrast, an axon carries the electrical signals away from the cell body to transmit them to other neurons or target cells (Silva, 2009). Axons are covered by a protective layer called the myelin sheath, which is composed of specialized cells called oligodendrocytes in the CNS and Schwann cells in the PNS (Poitelon, Kopec, & Belin, 2020). The myelin sheath acts as an insulating layer that prevents the leakage of electrical signals from the axon, allowing for faster and more efficient transmission of action potentials (Stadelmann et al., 2019). The myelin sheath achieves this by forming small gaps, known as nodes of Ranvier, along the length of the axon (Santos, Huffman, & Fields, 2022). These nodes allow the action potential to "jump" from one node to the next, a process called saltatory conduction, which significantly speeds up the transmission of signals (Susuki, 2010).

The CNS is made up of grey matter and white matter. Grey matter forms the outside layer of the brain (cerebral cortex) and is composed of cell bodies, dendrites, and unmyelinated axons, whereas white matter is found in the inner layer of the cortex and primarily consists of long-range bundles of myelinated axonal fibers that connect different regions of the brain (Budday et al., 2015; Buyanova & Arsalidou, 2021). Research suggests that axons in white matter are highly vulnerable to traumatic injury because of their long projections (Narayana, 2017).

1.1.2 White matter damage following mTBI

White matter fibers in the brain are particularly susceptible to damage from impact-acceleration forces, such as those experienced in mTBI (Armstrong et al., 2016). This is because the long axonal projections that make up white matter tracts can be damaged by torsion, tension, and compression forces during head trauma (Mierzwa et al., 2015). The primary concern associated with mTBI-induced white matter injury is diffuse axonal injury (DAI), which involves widespread damage to axons in white matter tracts (Armstrong et al., 2016). DAI is caused by a combination of rotational, acceleration, and deceleration forces induced on the brain after impact, resulting in shearing and stretching of axons (Johnson et al., 2013). This leads to axonal dysfunction or disconnection between neurons in white matter structures (Sharp et al., 2014) and can trigger a series of metabolic disturbances known as the neurometabolic cascade (i.e., biochemical and physiological events) (Giza & Hovda, 2014).

1.1.3 Neural dysfunction

Following mTBI, there is an increased depolarization of neurons, leading to an influx of calcium and sodium ions and an efflux of potassium ions (Giza & Hovda, 2001). This imbalance in ionic gradients can result in the disproportionate release of excitatory neurotransmitters, such as glutamate (Giza & Hovda, 2014; Kamins & Giza, 2016). Glutamate, in particular, is known to have vasoactive properties and can induce constriction of cerebral blood vessels (Gennarelli et al., 1982). This vasoconstriction can reduce cerebral blood flow. In addition, the inflammatory response triggered by DAI can also contribute to the reduction in cerebral blood flow. Following an mTBI, activation of microglia and astrocytes occurs, which release pro-inflammatory cytokines and chemokines (Loane & Kumar, 2016). These inflammatory mediators can cause endothelial dysfunction and impair the normal regulation of cerebral blood vessels, leading to a decrease in cerebral blood flow (Smith et al., 2023). Furthermore, mTBI can also impact glucose metabolism, leading to a state of energy dysfunction in the injured brain (Xu et al., 2021). The brain is highly dependent on glucose as its main energy substrate, and any disruption in glucose metabolism can have significant consequences (Mergenthaler et al., 2013). Clinical studies have shown that mTBI is associated with increased cerebral glucose utilization during the acute phase of injury (Bouzat et al., 2014). This enhanced glucose utilization is believed to be a compensatory mechanism to meet the increased energy demands of the injured brain (Karelina & Weil, 2016). However, this acute phase is followed by a sustained period of reduced glucose utilization, leading to a state of energy crisis (Giza & Hovda, 2001).

The neurometabolic changes that occur after mTBI usually exert widespread effects within the brain, which manifest in a variety of clinical signs and symptoms including impairment in memory, attention, and cognition (Giza & Hovda, 2001).

1.1.4 Clinical symptoms of mTBI

Clinical symptoms associated with mTBI can be categorized into several clusters. One study identified five symptom clusters in mTBI patients: post-traumatic headache/migraine, nausea, emotional/affective, fatigue/malaise, and dizziness/mild cognitive impairment (Hoffer et al., 2016). Another study documented symptoms in multiple domains, including physical (headache, tinnitus, dizziness), cognitive (memory, concentration), and behavioral (depression, anxiety, irritability) (Manners et al., 2016). Persistent symptoms commonly reported by mTBI patients include headache, memory loss, concentration difficulties, depression, and cognitive impairment (Gosset et al., 2022). Studies have also identified impairments in sensorimotor and physiological variables, including postural control, oculomotor function, and sleep, in people with a history of mTBI (Baldassarre et al., 2015). The manifestation of symptoms after mTBI can vary from person to person, with some symptoms appearing immediately following the injury and others taking days or weeks to emerge (Prince & Bruhns, 2017). It is important to note that while most symptoms resolve within the first two weeks after the injury, 15-40% of patients may experience prolonged post-concussion symptoms for months or even years (Baldassarre et al., 2015; Dischinger et al., 2009; McInnes et al., 2017). Overall, the clinical symptoms of mTBI are diverse and can have a significant impact on an individual's physical and psychological well-being.

1.2 Visual Perception

The visual world we consciously perceive is not a direct reflection of the raw visual information received by the retina. Instead, our perception involves internal processes and mechanisms that organize and interpret visual information, allowing us to create a coherent and meaningful perception of the world (Uhlhaas & Mishara, 2006; Uhlhaas & Silverstein, 2005). This phenomenon is known as perceptual organization, and refers to the ability to apply structure and organization onto incoming sensory information (Sarkar et al., 1993).

Perceptual organization, according to Gestalt psychologists, involves grouping visual elements based on principles of proximity, similarity, closure, continuity, good continuation and common fate (Behrmann & Kimchi, 2003). These principles facilitate the organization of visual information within an image or stimuli. Furthermore, perceptual organization is influenced by both bottom-up and top-down processing (Quinn & Bhatt, 2009). Bottom-up processing refers to the use of incoming sensory information from the environment to guide attention and perception (Itti & Koch, 2001). In contrast, top-down processing relies on prior knowledge, expectations, and context to guide attention and interpretation of visual stimuli (Gilbert & Li, 2013). Research has demonstrated that top-down processing plays a crucial role in perceptual organization by limiting the number of object representations and directing attention towards relevant features (Bar, 2003; Gilbert & Li, 2013; Gow et al., 2008; Sussman et al., 2016; Teufel & Nanay, 2017), enabling efficient and rapid processing of perceptual stimuli (Gilbert & Li, 2013). Therefore, deficits in top-down processing can result in difficulties integrating and interpreting sensory information effectively. Such deficits disrupt the flow of information from higher-level brain regions to lower-level sensory areas, impairing overall perceptual organization abilities (King et al., 2017). According to Gilbert and Li (2013), top-down processing involves the activation of high-level information in the prefrontal cortex, which is then back-projected to the temporal cortex for integration with bottom-up processes. This mechanism allows for the rapid activation of expectations and interpretations about the input image, reducing the number of object representations that need to be considered (Bar, 2003). Therefore, when top-down processing is impaired, this rapid mechanism may be disrupted, further hindering the ability to integrate and interpret sensory information in a meaningful way, leading to difficulties in perceiving the overall structure of a visual stimulus.

Visual illusions are commonly used in research to investigate perceptual organization (Notredame et al., 2014). These illusions offer valuable insights into how our perceptual system interprets and organizes sensory information, revealing the discrepancies between the physical world and our perceptual interpretation. The perception of visual illusions has proven to be a valuable tool for examining the automatic integration of global information, as many illusions arise from misjudgements in length, size, or orientation due to the inability to disregard surrounding visual information (Palomares et al., 2009). A key feature of a mature and fully developed nervous system is the ability to experience visual illusions (Ciszewski, Wichowicz, & Zuk, 2015; King et al., 2017). In this regard, the inability to perceive an illusion could be seen as a deficiency or impairment (Ciszewski, Wichowicz, & Zuk, 2015). For example, Horton and Silverstein (2011) found that the Ebbinghaus illusion was not perceived by patients with schizophrenia. The reduced perception of this illusion was suggested to be caused by a disruption in top–down processing, which led to an inability to perceive the illusion (Ciszewski, Wichowicz, & Zuk, 2015; King et al., 2017; Nakashima & Sugita, 2018; Rashal, Cretenoud, & Herzog, 2020). Essentially, these findings suggest that patients with schizophrenia perceived the illusion as its verdical representation, relying exclusively on direct sensory input without being influenced by prior knowledge. This indicates that this top-down process, which is responsible for "filling in the gaps" and making sense of ambiguous figures, does not occur in individuals with schizophrenia. Consequently, their perception of the illusion corresponds to its actual reality, unaffected by cognitive biases or expectations (Carbon, 2014; Notredame et al., 2014).

1.2.1 Global and Local Processing

The concept of 'Forest before the Trees', also known as global processing bias (i.e., global precedence), refers to the cognitive tendency to perceive the whole before recognizing individual parts (Navon, 1977). This cognitive phenomenon has been extensively studied through two primary modes of perceptual processing: global and local processing. Global processing involves focusing on the overall structure of a visual stimulus, whereas local processing involves attending to the individual constituents or details of a stimulus (Kimchi, 1992). The seminal work of Navon

(1977) provided the first empirical evidence for global processing bias, where global processing predominates over local processing (i.e., attention is directed to the overall structure of a visual stimulus first). In the Navon task, participants are presented with hierarchical stimuli, often a large (global) letter composed of smaller (local) letters. The global and local letters can either be congruent (i.e., the same letter) or incongruent (i.e., different letters). Participants are asked to identify either the global or local feature depending on the instruction. Navon (1977) found that participants identified the large letter more rapidly and accurately than the small letters. These findings have been consistently replicated across multiple studies, indicating that individuals typically have a tendency to process global features before local features (i.e., global processing bias) (Krakowski et al., 2016; Navon, 1977; Rezvani et al., 2020).

On the contrary, previous studies also suggest that individual differences in global and local processing biases exist (Gerlach & Starrfelt, 2018; Johnson, Waugh, & Fredrickson, 2010). One such influential factor is age, as demonstrated by a study by Kaldy and Kovacs (2003) on children's perceptual processing. They found that children, especially young ones, may have a stronger local processing bias (i.e., focus on the details of a visual stimulus first) compared to adults, as their cognitive abilities are still developing and are more attuned to salient details (Kaldy & Kovacs, 2003). This perspective is also supported by the finding that older adults tend to demonstrate a shift towards more local processing, possibly due to a decline in the ability to suppress irrelevant local information (Madden, 2007). Cultural background also plays a pivotal role in determining an individual's bias towards either global or local processing. For instance, cross-cultural research has highlighted significant differences in visual perception between individuals from Eastern and Western cultures. Studies have shown that individuals from Eastern cultures, such as China, Japan, and Korea, exhibit a more global processing style (Masuda & Nisbett, 2006; Nisbett et al., 2001). They tend to focus on the overall scene, while individuals from Western cultures, such as the United States and Europe, demonstrate a more local processing style, focusing on the attributes of an object (i.e., individual details of scene) (Kitayama et al., 2003; Nisbett & Miyamoto, 2005). These differences are thought to be rooted in cultural practices, socialization, and historical influences (Nisbett et al., 2001; Varnum et al., 2010). Conversely, research conducted by Davidoff, Fonteneau, and Fagot (2008) found that individuals from remote cultures displayed a stronger local processing bias. This may be due to greater reliance on specific, local information in societies with less technological dependence. Last, people with psychological disorders, such as autism spectrum disorder and schizophrenia, also demonstrate a strong bias for local information (Scherf et al., 2008; Tibber et al., 2015). Researchers have argued that this local processing bias may arise from reduced top-down processing, which leads to deficits in the integration of local details into a global context (Frith, 2004; Uhlhaas & Singer, 2014). Thus, while the global/local distinction remains a robust tool for assessing individual differences in visual perception, it is important to consider the diverse range of factors influencing this cognitive process.

1.2.2 Visual perception deficits following mTBI

Visual perception following mTBI has received far less attention compared to other cognitive processes (i.e., memory, attention, processing speed and executive functioning), yet evidence suggests that mTBI may impair the integration of visual information (McKenna et al., 2006). For example, Costa et al. (2015) reported perceptual organization impairments in people with TBI. They found people with TBI to be significantly worse in all measures of perceptual organization (perceptual grouping, figure-ground organization, parts in whole, and shape discrimination), indicating difficulties in integrating visual information into structured wholes. Building upon this, Radice-Neumann, Zupan, Babbage, and Willer (2007) reported that people with mTBI often have difficulty determining emotion from facial expressions (i.e., facial affect recognition). Studies on facial affect recognition indicate that individuals generally adopt a global processing strategy to evaluate facial expressions (Guo, 2012; Omigbodun & Cottrell, 2013). Therefore, Neumann, Keiski, McDonald, and Wang (2014) went on to further argue that deficits in facial affect recognition in people with mTBI may be the result of reduced global processing bias. Furthermore, the researchers found deficits in facial affect recognition in people with mTBI to be correlated with decreased activity in the right fusiform gyrus (an area of the brain responsible for processing global information).

Additionally, studies have consistently shown deficits in visual attention following mTBI (Alnawmasi & Khuu, 2022; Alnawmasi, Mani, & Khuu, 2022; Walz et al., 2021). Impaired selective attention may result in difficulties in integrating and organizing visual elements into coherent percepts. The inability to sustain attention can disrupt the processing of visual information over time, hindering the formation of a cohesive perceptual experience. That is, visual attention deficits may lead to difficulties in automatically attending to global or contextual information, resulting in a focus on local details and weakened ability to perceive the overall global structure of the stimuli (Alnawmasi et al., 2019). For example, Alnawmasi et al. (2019) found that individuals with mTBI displayed impaired ability to discriminate between glass patterns (i.e., visual stimuli made from multiple pairs of dots that give the percept of a coherent pattern). Given that the task required attention to the global (the glass pattern) rather than the local (the dots) features, Alnawmasi et al. (2019) speculated that increased attention to local information might have disrupted attention to the overall structure of the stimulus, which may have impacted object recognition abilities.

Taken together, these finding suggest that people with mTBI may have a reduced automatic tendency to process information globally. Consequently, this can result in fragmented perception and potentially impact how people with mTBI adapt to their environment and engage in important activities, such as work, sports, or recreation (Berger et al., 2016; Greenwald et al., 2012; Kersel et al., 2001). Thus, people with mTBI who experience impairments in perceptual organization may be more susceptible to injuries and recurrent TBIs (Armstrong, 2018; McCarty et al., 2002).

1.3 Movement automaticity

Movement automaticity refers to the ability to perform a motor skill without consciously attending to the mechanics of the movement itself (Bernstein, 1967; Wu, Hallet, & Chan, 2015). It is characterized by the smooth and efficient execution of movements, with minimal cognitive processing required (Wulf & Lewthwaite, 2010). According to Fitts and Posner (1967), automaticity of motor skill is achieved through the progression of three skill acquisition stages: cognitive, associative and autonomous stages. The cognitive stage is the initial phase of skill acquisition, where performers rely heavily on conscious control and attention to understand the skill and develop strategies for performing it accurately (van Halteren-van Tilborg, Scherder, & Hulstijn, 2007). In the associative stage, performers begin to refine their movements and begin to associate specific cues and feedback with the appropriate motor responses, allowing for more efficient and accurate execution of the skill (Martin et al., 2019). Finally, in the autonomous stage, following a period of practice, the movement becomes largely automatic and performed with minimal conscious effort and attention (Marinelli et al., 2017).

Movement automaticity is often assessed using a dual-task paradigm (Wu & Hallet, 2005), where individuals perform two tasks concurrently. This paradigm often involves performance of a primary motor task (e.g., walking), while simultaneously engaging in a secondary cognitive task (e.g., counting backwards in sevens). Efficient performance on dual-tasks relies on an individual's working memory capacity (Abernethy, 1988; Kal et al., 2015), which pertains to their ability to temporarily store and utilize information for cognitive tasks (Engle, 2002; Robison & Unsworth, 2015). When performing a dual task, it is argued that cognitive resources must be appropriately divided between the two tasks to ensure optimal performance (Pineda et al., 2023). However, if the demands of the two tasks exceed an individual's working memory capacity, deterioration in the performance of one or both tasks can occur (Nijober et al., 2016). Conversely, if both tasks are performed correctly during a dual task, it can be inferred that the motor task is automatic (Passingham, 1996, Wu & Hallet, 2005). Research suggests that as motor skills become automated, less attention and cognitive resources are needed to perform them; and thus, the remaining resources are sufficient to carry out the secondary task correctly (Wu, Hallet, & Chan, 2015).

1.3.1 Movement automaticity following mTBI

People with a history of mTBI typically demonstrate changes in movement variability (i.e., a change in movement execution from repetition to repetition) during dual-task conditions, similar to changes observed during the initial stages of motor learning (Fino, 2016; Springer & Gottlieb, 2017). This variability may result from disrupted executive functions, including working memory capacity, attention control, and cognitive flexibility, which are commonly impaired following mTBI (Ozen et al., 2013), and crucial for multitasking ability (Ackerman & Beier, 2007). While people with a history of mTBI may appear proficient in completing a task, such as walking while answering an arithmetic question correctly, alterations to the magnitude and structure of movement variability suggest a potential decrease in motor skill automaticity, thus requiring additional cognitive resources to maintain stability (Fino, 2016). Consequently, the increased cognitive demand for basic motor stability may hinder efficient allocation of cognitive resources to concurrent tasks and negatively impact an individual's ability to adapt to environmental constraints; ultimately, increasing the risk of further injury.

Furthermore, individuals with mTBI often exhibit altered interjoint coordination (i.e., the coordination of joint movements from the same limb to achieve a movement goal) when performing locomotor tasks concurrently with a cognitive task (Parker et al., 2006). This altered coordination is accompanied by reduced motor performance, including decreased lower extremity stiffness, slower gait velocity, and increased postural rigidity, increasing the potential for gait instability (Martini et al., 2021). These changes in motor performance reflect a loss of autonomous control of fundamental locomotion and postural stability, suggesting regression to the cognitive and associative stages of motor learning.

In addition, researchers have found that individuals with mTBI often modify their movement patterns to minimize the worsening of mTBI-specific symptoms and prevent reinjury (e.g., Fino et al., 2018; Martini et al., 2021). Similarly, individuals who have not had a previous history of mTBI, but have suffered an injury, often exhibit guarded movements. These movement behaviors can be attributed to psychological factors, such as fear or anxiety about movement-related pain or re-injury (Nishi et al., 2019; Vlaeyen et al., 1995). Research suggests that in such cases individuals may use conscious motor processing to control their movements to prevent pain or re-injury (e.g., Ellmers et al., 2021; Selfe et al., 2015). However, evidence also suggests, that use of conscious attention to control the mechanics of one’s movements can sometimes hinder rather than improve motor performance (e.g., Masters & Maxwell, 2008).

1.3.2 The Theory of Reinvestment

The theory of reinvestment (Masters, 1992; Masters & Maxwell, 2008; Masters, Polman, & Hammond, 1993) suggests that conscious attention to movements can involve the recall and application of task-relevant explicit/declarative knowledge. Specifically, reinvestment of declarative knowledge is thought to disrupt automated motor patterns, causing movement control to become less fluid (Masters & Maxwell, 2008).

The theory of reinvestment, however, suggests that the propensity to consciously engage in movements is a function of individual differences in personality and that a broad range of contexts have potential to invoke conscious control of movements (i.e., movement specific reinvestment), including psychological pressure to perform effectively, fear of injury or boredom (Masters & Maxwell, 2008). Evidence also suggests that an elevated propensity for conscious engagement in movements can occur in different populations in which movements may be disordered or difficult, such as people with Parkinson disease and stroke or the elderly (e.g., Masters, Pall, MacMahon, & Eves, 2007; Orrell, Masters, & Eves, 2009; Wong, Masters, Maxwell, & Abernethy, 2008). For instance, Masters et al. (2007) reported a positive correlation between the duration of Parkinson disease and reinvestment, suggesting that people with Parkinson disease become increasingly likely to consciously process their movements as the condition worsens, potentially as a consequence of continually trying to monitor and control their movements and/or as a consequence of becoming self-aware about the way in which they move. Similarly, Wong et al. (2008) discovered that older individuals with a history of falls have a higher propensity to reinvest than age-matched non-fallers. The authors argued that individuals who possess a fear of falling demonstrate a higher propensity to consciously process their movements, which may result in adoption of a more cautious gait pattern and subsequent disruption of the fluidity of walking. This potentially can increase the risk of future falls (Wong et al., 2008). Taken together, these results suggest that conscious attention to movements can result in disrupted performance. However, to our knowledge, the association between conscious motor processing and mTBI has not been investigated. Insights into this relationship could provide opportunities to optimize rehabilitation outcomes or reduce likelihood of further brain injury.

1.4 Biological motion perception

The perception of biological motion is facilitated by similar perceptual organization principles used to perceive stationary objects. In daily life, we are exposed to various movements that we can easily recognize and interpret. Our ability to perceive these movements is rooted in the frequency of exposure and prior experience, which ultimately shapes our perceptual expertise (Chang & Troje, 2009a; Loula et al., 2005). This notion is supported by studies using point-light display paradigms. Point-light display paradigms are a method of displaying movements by representing a few major joints on the human body as white points against a dark background (Klin et al., 2009). Despite the limited structural information, these displays are able to elicit the coherent percept of human body form, demonstrating the innate ability to organize sparse visual information into meaningful representations (Troje & Westhoff, 2006). The perception of biological motion from point-light displays is believed to be a result of observers' extensive visual experience with human motion (Troje & Westhoff, 2006). For example, Dittrich (1993) found locomotor actions (e.g., walking) to be more easily recognized than instrumental actions (e.g., repeatedly hitting a nail with a hammer) when presented in point-light displays. This finding has led researchers to propose that the ease of recognizing walking may be attributed to its frequent occurrence in the environment, making it a familiar action to individuals (Loula et al., 2005). In contrast, movements that are more complex or specific to certain activities, such as instrumental actions, may require a higher level of experience in order to be accurately recognized and understood.

For instance, within the domain of sports, movements are often considered much more specialized (i.e., specific to the sport). Research has consistently shown that expert athletes differ from novices in their visual perception abilities, with experts demonstrating superior performance in tasks requiring the detection and interpretation of sport-specific visual cues (Mann et al., 2007; Williams et al., 2011). This difference in performance can be attributed to domain-specific expertise, where experts acquire extensive knowledge and experience in their sport, allowing them to recognize and interpret relevant visual cues more efficiently. Furthermore, research suggests that the ability to accurately pick up postural cues or biological motion information from movements underpins effective anticipation (Jones & Miles, 1978; Williams & Jackson, 2019).

1.4.1 Anticipation in sport

Poulton (1957) defined anticipation as the ability to make accurate predictions from partial or incomplete sources of visual information. Expert athletes are more adept at recognizing and anticipating opponents' intentions based on subtle visual cues, such as body posture, limb movements, and eye gaze (Abernethy & Zawi, 2007; Cañal-Bruland & Mann, 2015). This ability to anticipate actions is thought to be driven by the experts' extensive experience, which allows them identify the most informative visual cues (Farrow & Abernethy, 2003; Gorman et al., 2012).

Along with experience, expert-novice differences can be attributed to the information pick up strategies employed. Experts tend to rely on a more holistic approach, utilizing a global processing strategy to gather information from various cues and sources (Huys et al., 2009). Novices, on the other hand, rely more on local processing strategies, focusing on individual cues or pieces of information (Abreu et al., 2012).

1.4.2 Global-Local processing in sports: expert-novice differences

Global processing plays a significant role in visual anticipation in sport. Expert athletes tend to rely on a more global perceptual approach when anticipating an opponent's movements, rather than relying solely on local information from specific body parts (e.g., Huys et al., 2009, Jackson & Mogan, 2007, Williams et al., 2009). Spatial occlusion paradigms have been used to assess local and global processing during anticipation in sport. These paradigms involve masking or removing visual cues to determine the anticipatory information used by viewers. For example, Huys et al. (2009) manipulated stick figure animations of a tennis player serving a shot in which select body segments were occluded. When information pertaining to the arm and racket was occluded, anticipation performance was impaired in both skilled and less-skilled players. However, only skilled players performance was further impaired when the hips, shoulders, and legs were occluded. The authors argued that skilled tennis players were reliant on more than one body segment to accurately anticipate the intentions of their opponent and, thus, picked up information in a more global manner compared to less skilled players. To further support this notion, Abernethy, Zawi, and Jackson (2008) investigated the abilities of expert and non-expert badminton players to predict the depth of an opponent's stroke. The participants were shown video displays or point-light displays depicting the hitting action. The results revealed that experts exhibited superior information pick-up from kinematic information and were more attuned to subtle cues from the lower body, which non-experts were not sensitive to. This further suggests that expert performers are better attuned to information distributed broadly across the body, allowing them to pick up more alternative sources of information to guide their actions.

1.4.3 Motion perception following mTBI

Although limited, research suggests that people with a history of mTBI have a deficit in processing motion information (Brosseau-Lachaine et al., 2008; Patel et al., 2011). For instance, Patel et al. (2011) investigated coherent motion (i.e., the ability to detect motion in a group of objects moving in varying directions) in people with and without a history of mTBI, and found that people with mTBI had difficulty detecting the coherent motion. The authors argued that these results suggest a deficit in the magnocellular/dorsal stream pathway, which is involved in all aspects of motion perception. Furthermore, Alnawmasi et al. (2019) assessed global motion processing using random dot kinematograms. Random dot kinematograms consist of a subset of dots moving coherently in one direction (horizontal or vertical – the signal dots) with the remaining dots moving in random directions (the noise dots). The observer judges the direction of coherent motion. Alnawmasi et al. (2019) found that people with mTBI had higher coherence thresholds (worse) for motion perception compared to the control group. The authors argued that global processing of motion requires integration of local visual information, so impairment in global motion processing may be due to a deficit in integrating local motion information.

Consequently, deficits in motion perception can put people recovering from an mTBI at an increased risk of sustaining further injury, especially when returning to sports. These deficits may affect an individual's ability to accurately perceive and respond to moving objects or stimuli, which is crucial in sports that involve fast-paced movements and quick reactions.

1.5 Summary and thesis outline

Perceptual organization deficits exist for both object and motion perception following mTBI. A general theme emerging from prior studies is that many of the tasks employed to examine visual integration following an mTBI have been unable to adequately distinguish whether a perceptual bias for local over global elements exists. Thus, the aim of this thesis was to examine whether people with a history of mTBI demonstrate atypical local or global processing, using robust scientific methodologies.

Visual illusions have previously been used to measure the automatic tendency to perceptually group visual features into coherent, whole objects. That is, in order to perceive the illusory effect, one must view all elements of the stimuli as a whole. Therefore, an individual who processes information locally rather than globally would not be susceptible to the illusion. Visual illusion susceptibility has yet to be examined in people with a history of mTBI; therefore, in Experiment 1, which is reported in Chapter 2, we used two types of size-contrast illusions (the

Ebbinghaus illusion and the Müller-Lyer illusion) to investigate whether people with mTBI are more likely to process the local details of a stimulus.

Researchers often investigate a bias toward global or local information by using hierarchical global/local stimuli known as “Navon stimuli”. These stimuli consist of large letters (global stimulus) composed of small letters (local stimuli), and participants are instructed to identify either the larger letter or the smaller letters. This approach allows researchers to assess whether individuals demonstrate an automatic tendency to process the global picture (i.e., the overall structure) prior to local details. At present, there is no literature on visual processing of Navon hierarchical letters by people with a history of mTBI. Therefore, in Experiment 2 (Chapter 3), the Navon task was utilized to confirm the assumption that people with a history of mTBI have reduced global processing bias.

Previous research suggests that people with a history of mTBI exhibit a reduced tendency to automatically process visual information in a global manner. That is, rather than perceiving visual stimuli as cohesive wholes, they are more likely to process them in fragmented parts. Consequently, these individuals might also apply this decomposed processing style to their movements, leading to an increased inclination for conscious processing, which can potentially result in inefficient or disrupted movement during skill execution. Therefore, in Experiment 3 (Chapter 4), we examined the propensity for conscious movement processing in people with and without a history of mTBI using the Movement Specific Reinvestment Scale (MSRS).

Experiment 4 (Chapter 5) was conducted in an attempt to apply the results observed in Experiments 1 and 2 to more real-world scenarios. Expert athletes demonstrate a global processing preference when anticipating the movements of their opponents (Hirai & Senju, 2020; Smeeton et al., 2019). That is, they rely on simultaneous processing of multiple cues for successful anticipation (Chang & Troje, 2009b; Huys et al., 2009). Therefore, in this final study, expert rugby players with and without a history of mTBI were required to anticipate the final running direction of an opponent changing direction (with or without deception). It was hypothesized that people with a history of mTBI utilize a local perceptual strategy, so they will face challenges in detecting relevant cues necessary for successful anticipation. This is because locally processing individual sources of information generally takes longer, potentially limiting the amount of information picked up for anticipation. We therefore expected people with mTBI to demonstrate poorer response accuracy and slower response times than controls.

In the final chapter (Chapter 6), the findings are summarised and discussed with regard to relevant research in the mTBI population. Practical applications for rehabilitation are provided and future directions for research are considered. A flow diagram providing an overview of the thesis is shown in Figure 1.

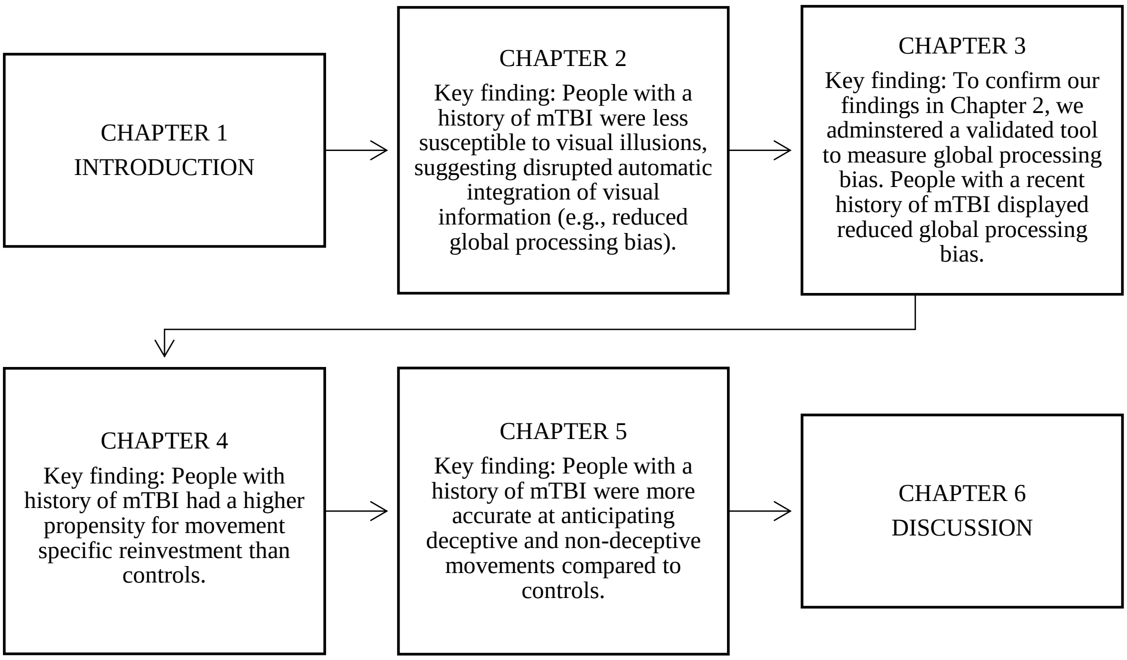

Figure 1. A flow diagram providing an overview of the thesis outline.

Chapter 2

Experiment 1: Reduced influence of perceptual context in mild traumatic brain injury is not an illusion[2]

2.1 Abstract

Perceptual grouping is impaired following mild traumatic brain injury (mTBI). This may affect visual size perception, a process influenced by perceptual grouping abilities. We conducted two experiments to evaluate visual size perception in people with self-reported history of mTBI, using two different size-contrast illusions: the Ebbinghaus Illusion (Experiment 1a) and the Müller-Lyer illusion (Experiment 1b). In Experiment 1a, individuals with mTBI and healthy controls were asked to compare the size of two target circles that were either the same size or different sizes. The target circles appeared by themselves (no-context condition), or were surrounded by smaller or larger circles (context condition). Similar levels of accuracy were evident between the groups in the no-context condition. However, size judgements by mTBI participants were more accurate in the context condition, suggesting that they processed the target circles separately from the surrounding circles. In Experiment 1b, individuals with mTBI and healthy controls judged the length of parallel lines that appeared with arrowheads (context condition) or without arrowheads (no context condition). Consistent with Experiment 1a, size judgements by mTBI participants were more accurate in the context condition. These findings suggest that mTBI influences size perception by impairing perceptual grouping of visual stimuli in near proximity.

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[2] Based on: **Sidhu, A.,** Uiga, L., Langley, B., & Masters, R.S.W. (2024). Reduced influence of perceptual context in mild traumatic brain injury is not an illusion. *Scientific Reports*

2.2 Introduction

Mild traumatic brain injury (mTBI), also commonly known as concussion, is a major public health concern affecting 42 million people worldwide each year (Gardener & Yaffe, 2015). mTBI is the result of external biomechanical forces (accelerative-decelerative forces) transmitted to the head, neck, or body, either through direct impact (e.g., head-to-head collisions) or indirect rotational forces (e.g., whiplash type injuries from tackling or a car accident) (Deschamps et al., 2022; Mayer et al., 2021). These biomechanical forces can induce tensile and shearing stress on the axonal fibers within the white matter tracts, resulting in diffuse axonal injury (DAI) (Namjoshi et al., 2021), which in turn can initiate a neurometabolic cascade (Giza & Hovda, 2001; Giza & Hovda, 2014) of neurochemical, ionic, and metabolic changes that disrupt normal communication within the brain (Charek et al., 2020; Di Battista et al., 2018; Khurana & Kaye, 2012; Leddy et al., 2012).

Given that approximately half of the brain's neural pathways are dedicated to vision, the visual system is particularly vulnerable to shearing injury following mTBI (Galetta et al., 2015). As a result, considerable attention has been drawn to a variety of visual impairments associated with mild traumatic brain injury (mTBI) (Greenwald, Kapoor, & Singh, 2012; Ma et al., 2016; Sharp, Scott, & Leech, 2014), including defects in visual acuity (Armstrong, 2018), blurred vision (Greenwald, Kapoor, & Singh, 2012), deficits in accommodation (Ventura, Balcer, & Galetta, 2014), and binocular disparity (Schimidtmann et al., 2017). However, little attention has been given to the perception of visual stimuli or the integration of visual information following mTBI.

Physiologically, the process of integrating individual elements in a visual image into a unified percept, a concept known as perceptual organization, is mediated by horizontal connections in the early visual cortex (V1) (Gowen et al., 2020). These horizontal connections, formed by the axon collaterals of pyramidal neurons in layer 2/3 of the visual cortex, run parallel to the surface of the brain. They connect neurons with similar response characteristics, such as preferred orientation, and play a crucial role in integrating information from separate parts of the visual field. More specifically, the V1 receives direct input of visual information from the environment and modulates it through horizontal connections in a feedforward fashion from low level visual areas to higher level areas (Gowen et al., 2020). Such organization allows the perception of visual stimuli to be context-specific, whereby the neural response to a visual stimulus depends on the surrounding stimuli or background (Schwartz, Hsu, & Dayan, 2007). For instance, when perceiving and judging attributes such as size, location or orientation of an object, the visual system often automatically takes into account surrounding elements in the visual scene (Walter & Dassonville, 2008). This integration of visual information functions in accordance with the Gestalt grouping principles (Kimchi, Behrmann, & Olson, 2003; Quinn, Brown, & Streppa, 1997; Todorovic, 2008; Wagemans et al., 2012). The Gestalt principles refer to specific ways in which humans automatically and holistically group visual features into coherent, whole objects and backgrounds (Koffa, 1935). The principles include grouping by proximity, similarity, good continuation, common fate and connectedness (Todorovic, 2008).

It has been proposed that individuals with mTBI may demonstrate deficits in perceptual organization (Costa et al., 2015). For instance, individuals with mTBI are reported to perform worse than controls on tasks that rely on grouping local elements into global wholes, such as perception of glass patterns (Alnawmasi et al., 2019), and contour integration (Ruiz et al., 2019). Furthermore, mTBI subjects were impaired at identifying circles formed by collinear Gabor elements embedded in a field of randomly oriented elements (Ruiz et al., 2019). However, a limited number of studies have examined the principles of perceptual organization following mTBI, emphasizing the need for further research in this area to gain a deeper understanding of the mechanisms underlying visual perception in this population.

The aim of the present study was to examine perceptual organizational abilities in mTBI using Gestalt grouping principles. Of the five Gestalts principles, the law of proximity is considered one of the most important grouping principles of perceptual organization (Im, Zhong, & Halberda, 2016). The principle of proximity states that when elements are in close proximity to one another, they tend to be perceived as single, cohesive group (Pomerantz & Schwaitzberg, 1975, Todorovic, 2008; Wagemans et al., 2012). A well-known example of grouping by proximity is size-contrast illusions (e.g., Ebbinghaus illusion, Müller-Lyer), in which the appearance of a target stimulus (e.g., length, width or diameter) is distorted by the surrounding or attached context (e.g., de Fockert et al., 2007; Lamy, Segal, &

Ruderman, 2006; Parron & Fagot, 2007). For instance, in the Ebbinghaus illusion the perceived size of a central target is significantly altered by the sizes of a set of surrounding circles (i.e., appears smaller when surrounded by larger circles, appears larger when surrounded by smaller circles) because healthy individuals tend to process the size of the target circle in relation to the surrounding circles. A similar effect can be observed in the Müller-Lyer illusion, where the perceived length of a line is influenced by the orientation of the arrowheads attached to it. Specifically, when the arrowheads point inwards, the line appears longer compared to when the arrowheads point outwards (Predebon, 2004). This effect is argued to be caused by the closer spatial proximity of the inward-pointing arrowheads to the shaft (Predebon, 2004), as individuals often focus on comparing the size of the whole figure rather than the length of the two lines (Rock, 1975). In other words, healthy individuals exhibit a globally oriented perceptual style when perceiving neighbouring objects in their visual field (Navon, 1977). Conversely, individuals with a deficit in perceptual grouping (i.e., unable to group individual features into a whole) display a more locally oriented perceptual style. This results in reduced susceptibility to visual illusions as a consequence of focusing only on the target and the parts of the inducers that are located in its close proximity (Bölte et al., 2007; de Fockert et al., 2007; King et al., 2017).

Thus, the study of size-contrast illusions is of strong heuristic value when examining perceptual grouping abilities in individuals with mTBI. To the best of our knowledge, visual illusion susceptibility has yet to be examined in mTBI. As a potential method for determining the extent to which perceptual organization is impaired in mTBI, we investigated whether individuals who had sustained a recent mTBI use the Gestalt principle of proximity when viewing size-contrast illusions. We hypothesized that if individuals with mTBI have impaired perceptual grouping abilities', as suggested by atypical perceptual organization (Costa et al., 2015), then they might demonstrate decreased susceptibility to size-contrast illusions than controls (i.e., more accurate at size judgements). Conversely, if individuals with mTBI do use the Gestalt principle of proximity, we would expect them to be susceptible to size-contrast illusions. To test this hypothesis, we conducted two laboratory experiments in which we asked people with and without self-reported mTBI to make perceptual judgments of the Ebbinghaus illusion (Experiment 1a) and the Müller-Lyer illusion (Experiment 1b).

2.3 Experiment 1a

In Experiment 1a, we investigated the effects of surrounding context on size perception using the Ebbinghaus illusion in individuals with mTBI compared to healthy controls. The Ebbinghaus illusion task assesses how individuals' size perception is sensitive to contextual features (Doherty, Tsuji, & Phillips, 2008; Phillips, Chapman, & Berry, 2004). In a series of forced-choice judgments, participants were asked to determine whether two 'target' circles presented side by side on a computer screen were the same size or different. In the context condition, the target circle was surrounded by smaller or larger circles that created a context with potential to alter discrimination of its size.

2.4 Method

2.4.1 Participants

Due to Covid-19, the study was conducted entirely online, using opportunistic convenience sampling. A total of 85 people responded to an email request to participate in the study. Participants included 24 mTBI (14 females, 10 males; mean age = 18.75 years, SD = 1.74 years), and 61 healthy controls (31 females, 30 males; mean age = 20.15 years, SD = 5.53 years). To be included in the mTBI group, participants were required to self-report ≥1 head injury within the last 12 months (see Section 2.4.2 for assessment of mTBI history). [3] To be included in the control group, participants were required to self-report no significant head injury history. Individuals using psychoactive medications or with psychiatric conditions, were excluded from the experiment. All participants had normal or corrected-to-normal vision. Normal or corrected-to-normal vision was defined as the ability to see clearly, either naturally or with the help of corrective lenses (glasses or contact lenses). This was determined through self-report. The experimental protocol was approved by the University of Waikato Ethics Committee and all participants provided informed consent electronically. Participants completed the experiment online and were advised that they were free to withdraw from the experiment at any time by closing the browser

[3] The 12-month cut-off period for the mTBI group was established based on research by Losoi et al. (2016), which indicates that most individuals typically require up to 12 months to recover from mTBI.

2.4.2 Assessment of mTBI history

Diagnosis of mTBI was defined as a traumatic brain injury caused by a direct blow to the head, face, neck, or elsewhere on the body, resulting in the onset of neurological change or impairment. Detailed mTBI history was ascertained using the Ohio State University Traumatic Brain Injury Identification Method (OSU TBI-ID). The OSU TBI-ID is a standardized procedure to elicit the lifetime history of TBI (Corrigan & Bogner, 2007). The measure consists of 11 items that measure the presence of historical TBI, cause of TBI, length of loss of consciousness and age of first and last occurrence of loss of consciousness. Participants in this experiment completed an online, self-administered version of the OSU TBI-ID, previously validated by Lequerica et al. (2018).

2.4.3 Apparatus and Stimuli

The experiment was created using the OSWeb extension of OpenSesame (Mathôt, Schreij, & Theeuwes, 2012), an experiment builder available online (https://osdoc.cogsci.nl/). The experiment was then imported into a JATOS (Just Another Tool for Online Studies) server (Lange, Kühn, & Filevich, 2015) where it was hosted and the data was stored. Participants were provided a link to the experiment and were instructed to use their personal laptop or computer. In each stimulus slide, two white target circles were presented in horizontal orientation on a black background. The target circles appeared either with surrounding inducer circles (context condition) or without surrounding inducer circles (no context condition) (see Figure 2). The center-to-center distance between the targets was 2.2 cm. In the context condition, one target circle was surrounded by 6 larger inducers (2.5 cm in diameter), whereas the other target circle was surrounded by 8 smaller inducers (0.3 cm in diameter). The side of the stimulus slide on which the smaller and larger surrounding inducers appeared was counterbalanced. In both the context and no context conditions, the target circles were either identical in size (same size condition) or different in size (different size condition) and ranged in size from 1.3, 1.5 or 1.7 cm. The position of the differently sized target circles (left / right) was counterbalanced in the different size condition. In the same size condition, there were 6 combinations: 3 size pairs (1.3-1.3 / 1.5-1.5 / 1.7-1.7) x 2 target-inducer pairs (large-small / small-large), and in the context different size condition, there were 8 combinations: 2 size pairs (1.3-1.5 / 1.5 - 1.7) x 2 target-inducer pairs (large-small / small-large) x 2 positions (left / right). Participants completed both context conditions twice, thus completing a total of 28 trials with context. In the no context same size condition, there were 3 combinations: 3 size pairs (1.3-1.3 / 1.5-1.5 / 1.7-1.7), and in the no context different size condition, there were 4 combinations: 2 size pairs (1.3-1.5 / 1.5-1.7) x 2 position (left / right). Participants completed the no context condition four times, in order to match the number of trials in the context condition. Each stimulus slide remained on the screen until the participant responded (or for a maximum of 3 seconds). In sum, participants completed 56 trials of the side-by-side comparison task (28 trials with context, 28 trials without context). Trials were presented in a randomized order via a JATOS randomisation algorithm.

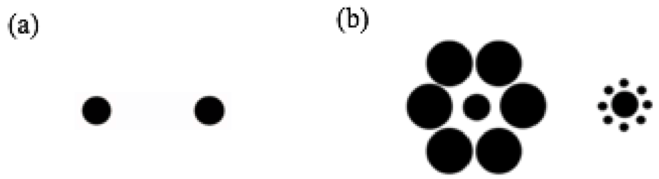


Figure 2. Examples of the stimuli used in the no context condition (Panel a) and the context condition (Panel b). In both conditions, the target circles are the same size. However, in the context condition (Panel b), the target circle on the left typically appears smaller than the target circle on the right (Ebbinghaus illusion).

2.4.4 Measures

A two-alternative forced choice paradigm was used, in which the participant had to decide whether the two target circles appeared the same or different in size. Participants recorded their answer by pressing the “A” key (same size) or the “L” key (different size) on the keyboard. The participants were not informed if an answer was correct or incorrect.

2.4.5 Procedure

Participants opened an online link, which directed them to a participant information sheet containing all study information and an electronic consent form. After providing consent, participants completed the Ohio State University Traumatic Brain Injury Identification Method form, the Rivermead Post Concussion questionnaire,[4]and a general health questionnaire. All measures were self-reported online using the Qualtrics survey platform. Upon completion of the questionnaires, participants were then automatically linked to the experimental study, where they completed 6 practice trials followed by 56 experimental trials, during which they were instructed to indicate whether the circles that appeared on the screen were the same size (press the "A" key on the keyboard) or a different size (press the "L" key on the keyboard). The whole procedure took approximately 15 minutes. All methods were performed in accordance with the relevant guidelines and regulations.

2.4.6 Statistical approach

Accuracy was calculated by averaging the percentage of correct responses for each condition in each group of participants.[5] Shapiro-Wilks test was used to test for normality ($\alpha = 0.05$). Due to unequal sample sizes and a non-normal distribution ($p < 0.05$), a non-parametric approach was adopted. The factors were group (individuals with mTBI vs. controls) and condition (context vs. no context). Group differences in size judgements were assessed by Mann–Whitney U tests. Hedges *g* was used to calculate effect sizes where possible. Hedges *g* is similar to Cohen's d, but is recommended when groups have small or unequal sample sizes, as it provides an unbiased estimate by weighting the pooled standard deviation (Ellis, 2010). Data were analyzed using IBM SPSS Statistics for Windows, Version 26.0 (Armonk, NY). Statistical significance was set at $p < 0.05$.

2.5 Results

The mean percentage of correct responses in each group (mTBI, controls) across conditions (context, no context) is shown in Figure 3. Analysis revealed that individuals with mTBI were more accurate than control participants in the context condition (U = 414; Z = -3.107; p = .002; Hedges g = -.757), but not in the no context condition (U = 727; Z = -.049; p = .961; Hedges g = -.086).

[4] The Rivermead Post-Concussion Symptoms questionnaire was included to evaluate the presence and severity of post-concussive symptoms. However, this questionnaire was not included in the analysis as only a small percentage of particpants indicated the presence of symptoms.
[5] All participants with missing data were excluded from the analysis.

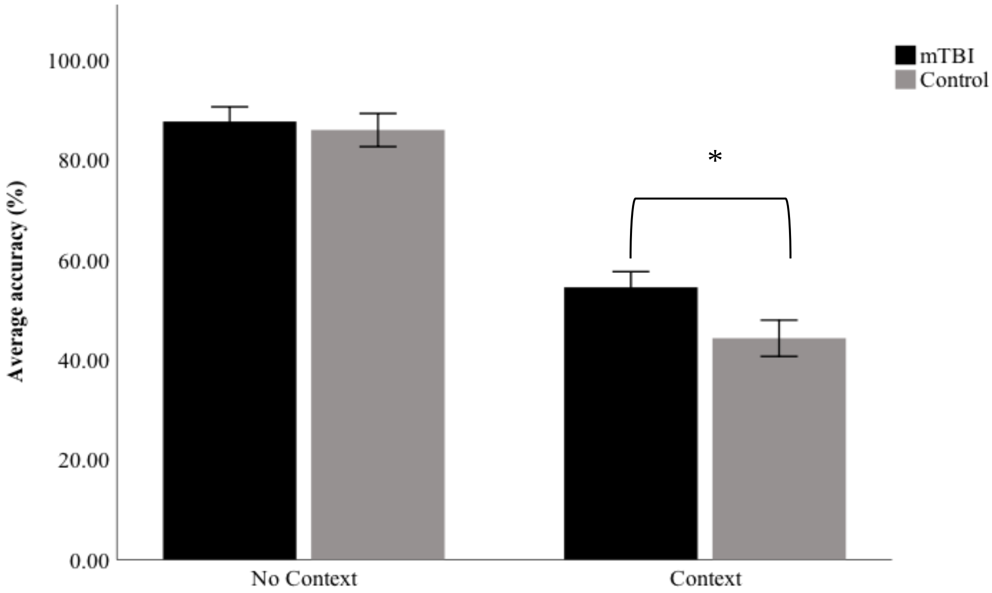


Figure 3. Mean discrimination accuracy (%) for each group as a function of context or no context. Error bars indicate ±1 SE of the mean. * indicates $p < 0.01$ level of significance.

2.6 Discussion

The two groups demonstrated a similar percentage of correct responses in the no-context condition. By contrast, the mTBI group exhibited significantly reduced susceptibility to the Ebbinghaus illusion, performing more accurately than controls in the context condition. These results suggest that people with mTBI may have more difficulty perceptually grouping surrounding context in their visual field. However, in order to better understand the nature of reduced contextual integration in people with mTBI, the use of another size-contrast illusion is necessary. Therefore, in Experiment 1b, we tested whether perceptual grouping abilities in people with mTBI differ when presented with the Müller-Lyer illusion.

2.7 Experiment 1b

In Experiment 2, the effects of surrounding context on size perception were investigated using the Müller-Lyer illusion in individuals with mTBI compared to healthy controls. The Müller-Lyer illusion consists of a set of parallel lines with opposing arrowheads on each end. When the arrowheads point outward, the line is generally perceived to be longer than when the arrowheads point inward. Consistent with the Ebbinghaus illusion, the Müller-Lyer illusion occurs because perception of the length of the lines is influenced by the attached visual context. In a series of forced-choice judgments, participants were asked to determine whether two lines presented parallel to each other on a computer screen were the same size or different.

2.8 Method

2.8.1 Participants

This study was conducted entirely online, using opportunistic convenience sampling. A total of 62 people responded to an email request to participate in the study. Participants included 19 individuals with mTBI (8 females, 11 males; mean age = 19.21 years, SD = 2.04 years), and 43 healthy controls (15 females, 28 males; mean age = 18.78 years, SD = 1.17 years). To be included in the mTBI group, participants were required to self-report ≥1 head injury within the last 12 months (see Section 2.8.2 for assessment of mTBI history). To be included in the control group, participants were required to self-report no significant head injury history. Individuals using psychoactive medications or with psychiatric conditions, were excluded from the experiment. All participants had normal or corrected-to-normal vision. The experimental protocol was approved by the University of Waikato Ethics Committee and all participants provided informed consent electronically. Participants completed the experiment online and were advised that they were free to withdraw from the experiment at any time by closing the browser.

2.8.2 Assessment of mTBI history

Assessment of mTBI history was identical to Experiment 1a.

2.8.3 Apparatus and stimulus

The experiment was created using the OSWeb extension of OpenSeseame, an experiment builder available online (https://osdoc.cogsci.nl/). The experiment was then imported into a JATOS server (Lange, Kühn, & Filevich, 2015), where it was hosted and the data was stored. Participants were provided a link to the experiment and were instructed to use their personal laptop or computer. In each stimulus slide, two parallel (white) lines were presented in horizontal orientation on a black background. The parallel lines appeared either with arrowheads attached at the ends of the line (context condition) or without arrowheads attached (no context condition) (see Figure 4). In the context condition, one line had inward-pointing arrows (> <) located at either end, and the other line had outward-pointing arrows at either end (< >). The horizontal line (top or bottom) on which the inward and outward-pointing arrows appeared was counterbalanced. In both the context and no context conditions, the parallel lines were either identical (same size condition) or different in length (different size condition) and ranged in length from 2.0, 2.5 or 3.0 cm. The distance between the two comparison lines was 1 cm. The position of each line in the different size condition was counterbalanced. In the context same size condition, there were 6 combinations: 3 size pairs (2.0-2.0 / 2.5-2.5 / 3.0-3.0) x 2 line-arrow pairs (inward-outward / outward-inward), and in the context different size condition, there were 8 combinations: 2 size pairs (2.0-2.5 / 2.5 – 3.0) x 2 line-arrow pairs (inward-outward / outward-inward) x 2 positions (top / bottom). Participants completed both context conditions twice, and thus performed a total of 28 trials with context. In the no context same size condition, there were 3 combinations: 3 size pairs (2.0-2.0 / 2.5-2.5 / 3.0-3.0), and in the no context different size condition, there were 4 combinations: 2 size pairs (2.0-2.5 / 2.5-3.0) x 2 positions (top / bottom). Participants completed both no context conditions twice. Each stimulus slide remained on the screen until the participant responded (or for a maximum of 3 seconds). In sum, participants completed 42 trials of the top-bottom comparison task (28 trials with context, 14 trials without context). Trials were presented in a randomized order via a JATOS randomisation algorithm.

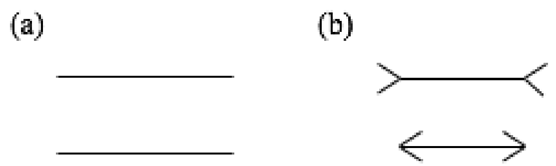


Figure 4. Example images of the two parallel lines in no context condition (Panel a) and context condition (Panel b). In both conditions, the parallel lines are equivalent in length. However, in the context condition (Panel b), perception of the length of the line is distorted by the presence of outward or inward pointing arrowheads at the ends of the line. The upper line is typically perceived to be longer than the bottom line, although the two lines are equal in length (Müller-Lyer illusion).

2.8.4 Measures

A two-alternative forced choice paradigm was used, in which the participant had to decide whether the two lines appeared the same or different in length. Participants recorded their answer by pressing the "A" key (same size) or "L" key (different size) on the keyboard. The participants were not informed if an answer was correct or incorrect.

2.8.5 Procedure

The general procedure for the main experiment was identical to Experiment 1a (see section 2.4.2). All methods were performed in accordance with the relevant guidelines and regulations.

2.8.6 Statistical analysis

Accuracy was calculated by averaging the percentage of correct responses for each condition in each group of participants.[6] The Shapiro-Wilk test was used to test for normality ($\alpha = 0.05$). Due to unequal sample sizes and a non-normal distribution ($p < 0.05$), a non-parametric approach was adopted. The factors were group (individuals with mTBI vs. controls) and condition (context vs. no context). Group differences in size judgements were assessed by Mann–Whitney U tests. Hedges *g* was used to calculate effect sizes where possible. Hedges *g* is similar to Cohen's d, but is recommended when groups have small or unequal sample sizes, as it provides an unbiased estimate by weighting the pooled standard deviation (Ellis, 2010). Data were analyzed using IBM SPSS Statistics for Windows, Version 26.0 (Armonk, NY). Statistical significance was set at $p < 0.05$.

2.9 Results

The mean percentage of correct responses in each group (mTBI, controls) across conditions (context, no context) is shown in Figure 5. Analysis revealed that individuals with mTBI were more accurate than control participants in the context condition (U = 251; Z = -2.40; $p = .016$; Hedges $g = -.714$), but not in the no context condition (U = 390; Z = -.335; $p = .737$; Hedges $g = -.151$).

[6] All participants with missing data were excluded from the analysis.

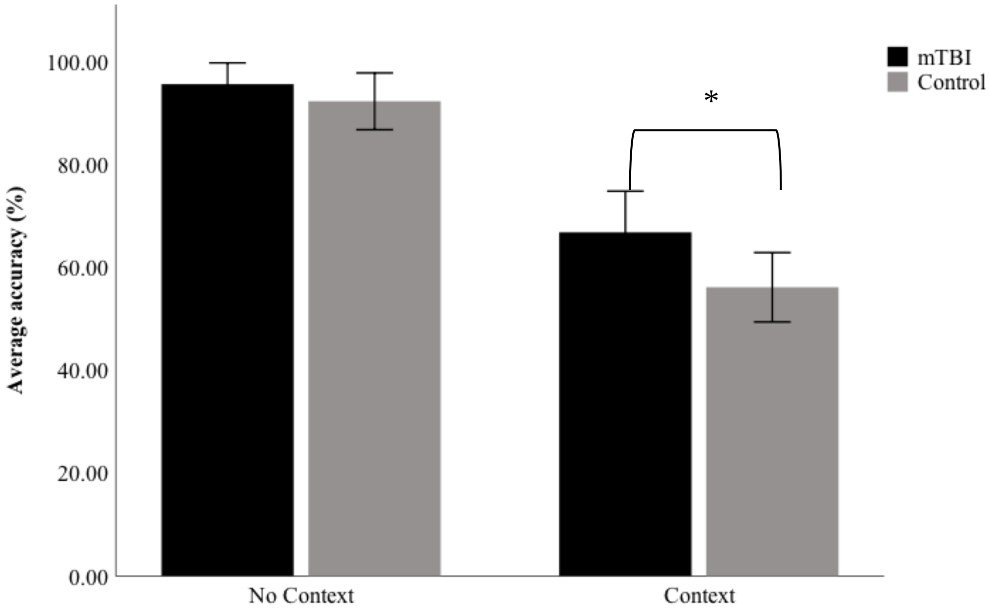


Figure 5. Mean discrimination accuracy (%) in each group as a function of context and no context. Error bars indicate ±1 SE of the mean. * indicates $p < 0.05$ level of significance in the group differences.

2.10 Discussion

In keeping with the findings in Experiment 1, participants in the mTBI group displayed more accurate size judgments than participants in the control group in the context condition, suggesting that those with mTBI were less susceptible to the Müller-Lyer illusion than participants without mTBI. This experiment provides further evidence that mTBI influences size perception by impairing perceptual grouping of visual stimuli in near proximity.

2.11 General Discussion

In two experiments, different size-contrast illusions (i.e., the Ebbinghaus illusion and the Müller-Lyer illusion) were used to examine visual size perception in participants with or without mTBI. Participants with self-reported symptoms of mTBI were found to display significantly better size-contrast judgments for both illusions, implying that they were less susceptible to the perceptual distortion that is typically caused by the illusion. These results suggest that participants in the mTBI group may not perceptually group the target stimulus with the nearby visual elements (e.g., context). Together, our results provide support for the hypothesis that individuals with mTBI have reduced ability to automatically group by proximity as a result of impaired perceptual organization of the visual field (i.e., processing of individual features of a visual stimuli). Intact perceptual grouping processes would have led to automatic grouping of the surrounding context used in each experiment, resulting in a normal visual illusion effect as observed in the control group.

Previous studies that have used size-contrast illusions have hypothesized that the grouping of contextual information is mediated by long-range connections between neurons of similar orientated stimuli (i.e., edges and lines) within the same visual area (Elder, Oleskiw, & Fruend, 2018). These long-range interactions can be related to the intrinsic horizontal connections of the visual cortex, which provide a substrate for integrating information between cortical areas to produce coherent perception (Elder, Oleskiw, & Fruend, 2018). However, with weakened or disrupted connections, visual perception becomes more local and less affected by the surrounding context (Gilbert & Li, 2013). For example, Káldy and Kovács (2003) found that four-year-old children performed more accurately in a visual size discrimination task than adults. The authors argued that the superior performance of young children may be attributed to the incomplete maturation of neural circuits that facilitate the integration of contextual information. It is possible that this may be a similar case for individuals with mTBI; that is, rotational forces induced during mTBI damage long-range connections, which results in reduced cortical integration across visual fields (Kurylo, Waxman, & Kezin, 2006; Ma et al., 2016). This raises the possibility that failures to form context-based interactions may lead to the same sort of global processing differences that are found in young children whose visual systems have not yet fully developed the circuitry to support long-range connectivity.

Cortical integration is mediated by a plexus of long-range connections that allow neurons to coordinate information across cortical regions (Kurylo, Waxman, & Kezin, 2006). The mechanisms involved in perceptual grouping consist of long-range horizontal connections among neurons in layers 2/3 of V1 and V2 (Kapadia et al., 1995), which facilitate center-surround interactions within the receptive fields, enable groupings of collinear oriented elements and contribute to early object formation (Chisum & Fitzpatrick, 2004; Kapadia et al., 1995; Palomares et al., 2009). Visual information is then relayed to ventral cortical areas such as V4 (extrastriate area), where it is further integrated into more complex representations of visual stimuli (Chisum & Fitzpatrick, 2004; Grossberg, Mingolla, & Ross, 1997;

Hess & Field, 1999; Palomares et al., 2009). Researchers have argued that mTBI can disrupt cortical processing, which may lead to impaired connections for cortical integration, making perceptual grouping, a process that integrates and coordinates information, particularly susceptible to disruption of cortical integration following mTBI (Kurylo, Waxman, & Kezin, 2006).

In the present study, our findings suggest that mTBI influences size perception by impairing perceptual grouping of visual stimuli in near proximity. This finding may help to explain why individuals with mTBI tend to perform poorly on visual perception tasks that rely on grouping multiple stimulus elements within the visual field; that is, when the ability to organize visual stimuli into meaningful patterns or structures is crucial for accurate perception. For example, one study showed that a small sample of adult patients with mTBI (n = 11) displayed impaired ability to discriminate between glass patterns (i.e., visual stimuli made from multiple pairs of dots, that give the percept of a coherent pattern), thought to be caused by widespread disruption in visual processing that extends to both major extra-striate visual cortex processing streams after axonal disruption (Alnawmasi et al., 2019). A contour integration study further showed that mTBI participants poorly integrated disconnected oriented elements into cohesive contours (Ruiz et al., 2019). This impaired performance was speculated to be caused by disruption of long-range connections and the authors suggested that multiple components of the ventral visual pathway, needed for shape and object analysis, may be affected by mTBI. Therefore, it is postulated that individuals with mTBI may exhibit impairments in effectively processing perceptual grouping cues (i.e., surrounding or attached contextual stimuli), which may enable them to perceive the individual features (i.e., the details) of a visual stimulus first, potentially leading to a reduction in higher-order visual functions (i.e., recognizing shapes and objects).

Our study has a number of limitations and its results should be interpreted with caution. First, the online opportunistic sampling procedure that we adopted in both experiments resulted in unequal sample sizes. Although the Mann-Whitney U test is robust to unequal sample sizes, non-parametric tests have lower power to detect true effects than parametric tests. Second, while the use of visual illusions provides a measure of how the brain perceptually groups visual information into a coherent percept, it is important to note that alternative explanations have been proposed regarding the perception of visual illusions. Some researchers have argued that reduced susceptibility to visual illusions could be due to weakened top-down processing (knowledge-driven processing, also known as predictive coding), which prevents higher-level information, such as context, from modulating initial perception (Rauss & Pourtois, 2013; Shea, 2015). In other words, the illusion is perceived as its true image based on incoming sensory information without involvement of prior memory stores (i.e., knowledge of physical attributes of the world). This argument is upheld in people with schizophrenia who appear not to utilize top-down processing and, thus, often demonstrate reduced susceptibility to illusions (Notredame et al., 2014). Therefore, it is possible that top-down processing could also be affected by mTBI and potentially cause abnormalities in the perception of visual illusions. Third, the use of self-report rather than medical diagnosis of mTBI is potentially a concern due to several reasons. Self-reported measures are based on subjective information, and participants may have recall bias, which can impact the accuracy of the reported time since the injury, number of mTBI sustained, and the symptoms experienced. Furthermore, self-reported measures may not fully capture the extent and complexity of symptoms associated with mTBI, as some symptoms may go unreported due to lack of awareness or understanding. Fourth, the online and cross-sectional design of the study limited our ability to examine individuals directly after sustaining an mTBI. Thus, we are unable to determine causality between mTBI and perceptual grouping. That is, other factors (i.e., recovery processes) associated with sustaining an mTBI may affect perceptual grouping mechanisms. This limitation is important to consider as it may not accurately reflect the acute stages of mTBI and may not be generalizable to the entire population of mTBI individuals. Therefore, a longitudinal study should be conducted to examine the evolution of perceptual grouping deficits in individuals with mTBI. This approach would involve initial assessment of perceptual grouping abilities immediately post-injury and repeated evaluations throughout the recovery period. Such studies would yield valuable insight into the nature and recovery of perceptual grouping deficits in mTBI.

In conclusion, the present findings provide evidence for impaired perceptual grouping of visual stimuli in near proximity among individuals with mTBI. This was reflected by better size discrimination accuracy in the context condition, which suggests that individuals with mTBI were less influenced by visual illusion effects because they were able to process the induced parts separately from the inducing context. That is, the mTBI group may not have shown the same precedence for global processing that has been found in healthy controls (Predebon, 2004); instead, they may be more likely to process the local features of a stimulus configuration first, as has been observed in people with autism (Bölte et al., 2007). However, to confirm the presence of a localized processing bias in individuals with mTBI, additional studies are necessary. Future work using local-global processing tasks such as the Navon task, could be utilized to examine how individuals with mTBI integrate and prioritize visual information. By manipulating the size and congruence of local and global features in visual stimuli, the Navon task can probe mechanisms underlying perceptual organization, cognitive biases and attention allocation. It is further warranted to explore these behavioral measures in conjunction with eye-tracking, electrophysiological or functional imaging measurements, to gain insight into how individuals with mTBI scan visual scenes, prioritize different features or objects, and the neural mechanisms associated with visual perception.

Chapter 3

Experiment 2: Reduced global processing bias and mild traumatic brain injury[7]

3.1 Abstract

Healthy individuals typically exhibit a global processing bias, which refers to processing information in a holistic or gestalt manner, focusing on the overall context prior to the individual details. The findings from Chapter 2 suggest, however, that individuals with a history of mild traumatic brain injury (mTBI) may not demonstrate the same global processing bias. Instead, they may exhibit a greater tendency to process the local features of a stimulus first. Experiment 3, therefore, examined whether people with a history of mTBI show a reduction in global processing. Participants (16 people with a history of mTBI within 12 months, 16 people with a history of mTBI beyond 12 months and 24 healthy controls) were

[7] Based on: **Sidhu, A.,** Uiga, L., Langley, B., & Masters, R.S.W. (2024). Reduced global processing bias and mild traumatic brain injury. *Scientific Reports*

presented with a Navon stimulus (a large letter that was made up of smaller letters) and were asked to identify either the overall shape of the letter (global) or the smaller letters making up the letter shape (local). Reaction time and accuracy were measured. People with a recent history of mTBI (within the last 12 months) displayed a reduced global processing bias. However, individuals who sustained their most recent mTBI over a year ago displayed the same global processing bias as healthy control participants. Taken together, these results suggest that global processing abilities may return to normal levels by one year after the injury.

3.2 Introduction

Specific deficits in visual–spatial perception, attention, and executive function have been observed following mild traumatic brain injury (mTBI) (Benassi et al., 2013; Zoccolotti et al., 2011). However, there is no consensus on the cognitive–perceptual mechanisms that might underlie these observed deficits. Studies have suggested that deficits might be due to a general failure of people with mTBI to perceive Gestalt (whole or global) aspects of stimuli (Alnawmasi et al., 2019; Costa et al., 2015; Neumann et al., 2016).

Visual perception operates according to a hierarchical processing model, which encompasses both global and local levels of analysis (Kimchi, 1992; Martinez et al., 1997). The global level involves processing information about the overall shape or structure of a visual stimulus, providing a holistic understanding of the scene. Conversely, the local level involves processing the individual components or details of the stimulus, allowing for a more detailed representation of the visual scene (Romei et al., 2011). Navon's "forest for the trees" phenomenon (Navon, 1977) suggests that individuals typically prioritize processing the global level prior to attending to the local level. Thus, it could be inferred that visual perception follows a progression from global-to-local processing when analyzing the visual environment.

To understand the dichotomy between global versus local processing, Navon (1977) developed a task that utilizes a hierarchical stimulus consisting of a large single letter comprised of smaller letters (e.g., a large H made up of small Hs). The stimulus could either be congruent, in which the larger letter is constructed from the same smaller letters (e.g., a large H from small Hs), or incongruent, in which the larger letter is constructed from different smaller letters (e.g., a large

H from small Ss). The Navon task, as it is best known, requires participants to either identify the larger letter and ignore the small letters (global level), or identify the smaller letters and ignore the large letter (local level). Past researchers have consistently demonstrated that when attention is required at the global level, response times are relatively fast and minimally impacted by interference from the local level, but when attention is required at the local level response times are slower with increased susceptibility to interference from global stimuli (Bendall & Thompson, 2015; Gerlach & Poirel, 2018; Navon, 1977). These findings suggest that the processing of global features takes precedence over processing the local features (global processing bias; Navon, 1977). In other words, individuals typically have an inclination to first attend to the global features of a visual scene before considering the local details. As a result, global stimuli are responded to more quickly than local stimuli, regardless of stimulus congruence. However, subsequent research has indicated that this finding is not universal and can be influenced by a number of factors. For example, reduced global processing bias has been associated with various mood states (i.e., depression, anxiety) (de Fockert & Cooper, 2014; Shilton, Laycock, & Crewther, 2019) and psychological disorders (i.e., schizophrenia and autism) (Scherf et al., 2008; Tibber et al., 2015).

Numerous behavioral and neuroimaging studies have indicated asymmetrical hemispheric activation during the processing of global and local information (Fink et al., 1997; Stankovic & Nešić, 2018; Yamaguchi et al., 2000). Specifically, it has been observed that the right hemisphere exhibits greater activation when analyzing global features, while the left hemisphere shows heightened activity when processing local features (Fink et al., 1997; Stankovic & Nešić, 2018; Yamaguchi et al., 2000). Moreover, research conducted on patients with brain lesions has demonstrated that individuals with right-hemisphere lesions tend to respond slower to global stimuli, whereas patients with left-hemisphere lesions respond slower to local stimuli (Lamb, Robertson, & Knight, 1990; Robertson, Lamb, & Knight, 1988).

A number of studies have associated mTBI with diminished right hemisphere functioning (Chen et al., 2004; McAllister et al., 2006; Muller et al., 2021). People with a history of mTBI have been reported to demonstrate reduced functional connectivity in the right frontal cortex (Graner et al., 2013; Hocke, et al., 2018), right dorsolateral prefrontal cortex (Chen et al., 2004; Chen et al., 2008;

Stemper et al., 2015; Witt et al., 2010), right parietal cortex (McAllister et al., 2006), right superior frontal gyrus (Zhang et al., 2022), and the right prefrontal cortex (Doshi et al., 2015). Given the proposed reliance on the right hemisphere for processing global-level features and the potential impairment of this hemisphere in people with mTBI, it is likely that those with a history of mTBI may exhibit a reduced global processing bias.

The global versus local processing bias has yet to be examined directly in mTBI; however, in Chapter 2 we used visual illusions to examine size-contrast judgments by people with mTBI. In two experiments, Chapter 2 found that people with mTBI exhibited greater accuracy when judging relative size in the Ebbinghaus and Muller-Lyer illusions, respectively, compared to controls. The authors argued that people with mTBI may process the central components (line/circle) independently of their perceptual context, and that this may be one manifestation of a more general disturbance in the integration of global contextual information in mTBI. Lack of susceptibility to visual illusions has been observed in other populations, including autistic people (Happé, 1996; Phillips et al., 2004) and young children (Kaldy & Kovacs, 2003), all of whom demonstrate a reduced global processing bias. Thus, the findings of Chapter 2 suggest that people with mTBI may demonstrate an atypical bias for local instead of global processing. Furthermore, Neumann, McDonald, West, Keiski, and Wang (2016) reported deficits in facial affect recognition in people with mTBI (i.e., poor recognition of emotions from facial expressions). This was correlated with decreased activity in the right fusiform gyrus, further suggesting that these deficits may be the result of impaired holistic face processing (i.e., integration of facial features into a gestalt representation). Together, the findings of Chapter 2 and Neumann et al. (2016) suggest that people with a history of mTBI may not demonstrate the typical global processing bias.

Thus, this experiment was designed to investigate if people with a history of mTBI demonstrate reduced global processing bias, by conducting the first direct test of local-global processing in people with a history of mTBI. We predicted that if individuals with a history of mTBI exhibit reduced global processing bias, then they will display a similar congruency effect for both the global and local task. This finding would suggest that people with a history of mTBI may lack the automatic tendency to prioritize global features when attending to visual scenes.

3.3 Method

3.3.1 Participants

A priori power analysis using G∗Power 3.1 (Faul et al., 2009) determined that to achieve 95% power, alpha of 0.05, with expected effect size of 0.25 (Chapter 2), the required sample size was 45. To account for a possible 20% attrition rate, a total of 56 participants were recruited. Participants included 16 individuals with a history of mTBI within 12 months (6 females, 10 males; 23.81 ± 7.77 years), 16 individuals with history of mTBI beyond 12 months (5 females, 11 males; 22.93 ± 4.42 years) and 24 healthy controls (15 females, 9 males; 21.33 ± 4.05 years).

To be included in the mTBI group, participants were required to self-report one or more incidents of head injury (see below for assessment of mTBI history). To be included in the control group, participants were required to self-report no significant head injury history. Individuals who self-reported current use of psychoactive medications or psychiatric conditions (diagnosed or undiagnosed), were excluded from the experiment. All participants had normal or corrected-to-normal vision. The experimental protocol was approved by the University of Waikato Ethics Committee and all participants provided informed consent electronically. Participants completed the experiment online and were advised that they were free to withdraw from the experiment at any time by closing the browser.

3.3.2 Assessment of mTBI history

For the purpose of this study, mTBI was defined as a traumatic brain injury caused by a direct or indirect blow to the head, face, neck, or other parts of the body, resulting in neurological changes or impairment. To obtain a comprehensive history of mTBI, the Ohio State University Traumatic Brain Injury Identification Method was adminstered (OSU TBI-ID) (Bogner & Corrigan, 2009; Corrigan & Bogner, 2007). The OSU TBI-ID is a standardized method that aims to elicit an individuals lifetime history of TBI. The questionnaire consists of 11 items that assess various aspects of TBI history, including the occurrence, cause of injury, and duration of loss of consciousness. Participants in this experiment completed an online, self-administered version of the OSU TBI-ID, previously validated by Lequerica et al. (2018).

3.3.3 Apparatus and stimuli

The experiment was created using the OSWeb extension of OpenSesame (Mathôt, Schreij, & Theeuwes, 2012), an experiment builder available online (https://osdoc.cogsci.nl/). The experiment was then imported into a JATOS (Just Another Tool for Online Studies; Lange, Kühn, & Filevich, 2015) server, where it was hosted and the data was stored. Consistent with Navon's original study (1977), participants were presented with a larger letter (i.e., H or S) composed of small letters (i.e., H or S). This created four types of stimuli, of which two were congruent (small and large letters were the same; i.e., a big H composed of small Hs or a big S composed of small Ss) and two were incongruent (small and large letters were different; i.e., a big H composed of small Ss or a big S composed of small Hs) (see Figure 6). Stimuli were presented as white letters, in one of the four corners of a black screen. Stimulus position was varied in order to prevent participants from adopting a local attention strategy in which they simply focused their attention on the same small region of the visual field on each trial (de Fockert & Cooper, 2014).

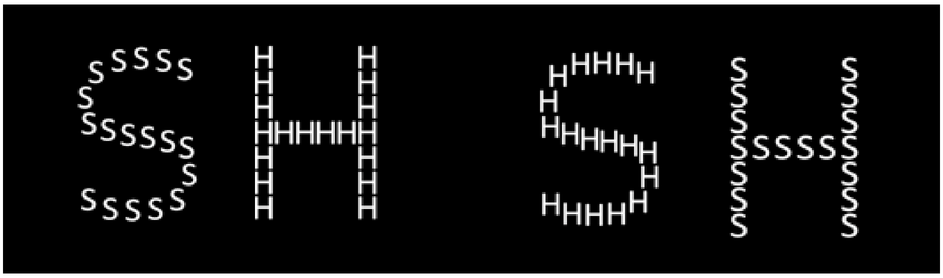


Figure 6. Examples of the stimuli used: Panel a, congruent condition; Panel b, incongruent condition.

3.3.4 Procedure

Participants opened an online link, which directed them to a participant information sheet containing all study information and an electronic consent form. After providing consent, participants completed the Ohio State University Traumatic Brain Injury Identification Method form, the Rivermead Post Concussion questionnaire, and a general health questionnaire. All measures were self-reported online using the Qualtrics survey platform. Upon completion of the questionnaires, participants were then automatically linked to the experiment. The experiment included two blocks of 48 trials: a global block in which participants were asked to determine the identity of the large (global) letter; and a local block in which participants were asked to determine the identity of the small (local) letters. Each block began with three practice trials, followed by 48 experimental trials. Half of the trials involved congruent letters and half of the trials involved incongruent letters. Trial type was randomized, and block order was counterbalanced between participants. Participants' task was to report the identity of the global (large) letter or of the local (small) letters as quickly and accurately as possible via a key press ("S" keypress for 'S', "H" keypress for 'H'). Response time and accuracy were recorded. The participant was not informed if an answer was correct or incorrect. Each trial started with a central fixation cross (1000 ms), followed by presentation of a stimulus (H or S), in one of the four corners of the screen. The stimulus remained on the screen for 2000 ms or until key press. Participants completed a total of 96 trials. The whole procedure took approximately 15 minutes.

3.3.5 Statistical analysis

Mean response accuracy and reaction time for correct responses were calculated for each participant.[8] Three-way repeated measures Analyses of Variance (ANOVA) were conducted to examine response accuracy and reaction time separately, using within-subject factors of Task (global / local) and Condition (congruent / incongruent) and a between-subject factor of Group (mTBI within 12 months / mTBI beyond 12 months / control). Follow-up analyses were conducted to further analyze significant interactions, using ANOVAs and t-tests. Statistical significance was set at $p < 0.05$. Effect sizes were calculated as partial eta squared (η_p^2), with values of 0.01, 0.06 and 0.14 used to indicate small, medium and large effects sizes, respectively. The results of the study were presented as mean ± SD.

3.4 Results

3.4.1 Reaction time

Figure 7 displays mean reaction times for each group as a function of task (global/local) and letter congruency (congruent/incongruent). Significant main effects were observed for Task, $F(1,53) = 313.466$, $p < .001$, $\eta_p^2 = .855$, Condition, $F(1,53) = 70.102$, $p < .001$, $\eta_p^2 = .569$, and Group, $F(1,53) = 3.230$, $p = .047$, $\eta_p^2 = .109$. There was an interaction between Task and Group, $F(2,53) = 8.908$, $p < .001$, $\eta_p^2 = .252$, between Condition and Group, $F(2,53) = 4.848$, $p = .012$, $\eta_p^2 = .155$, and between Task and Condition, $F(1,53) = 36.358$, $p < .001$, $\eta_p^2 = .407$.

[8] All participants with missing data were excluded from the analysis.

Additionally, there was an interaction between Task, Condition and Group, $F(1,53) = 3.277$, $p = .046$, $\eta_p^2 = .110$. To investigate the three-way interaction, two-way ANOVAs were conducted separately for each group, with Task and Condition as within-subject factors.

For the control group, there was a significant main effect of Task, $F(1,23) = 61.934$, $p < .001$, $\eta_p^2 = .729$, indicating that response times were faster during the global task (259.79 ± 100.75 ms) compared to the local task (415.28 ± 81.71 ms). There was also a significant main effect of Condition, $F(1,23) = 364.872$, $p < .001$, $\eta_p^2 = .941$, indicating that response times were faster during congruent trials (313.89 ± 86.34 ms) compared to incongruent trials (362.16 ± 85.31 ms). Additionally, there was a significant interaction between Task and Condition, $F(1,23) = 27.526$, $p < .001$, $\eta_p^2 = .545$, indicating a classic global processing bias in which response times were faster during the local task for congruent letters (371.12 ± 80.93 ms) compared to incongruent letters (459.44 ± 97.96 ms), $t(23) = -7.901$, $p < .001$, but not during the global task for congruent letters (254.69 ± 112.27 ms) compared to incongruent letters (264.88 ± 102.85 ms), $t(23) = -1.272$, $p = .216$.

For the mTBI within 12 months group, there was a significant main effect of Task, $F(1,15) = 6.105$, $p = .026$, $\eta_p^2 = .289$, indicating that response times were faster during the global task (263.59 ± 123.40 ms) compared to the local task (348.95 ± 100.08 ms). There was also a significant main effect of Condition, $F(1,15) = 20.739$, $p < .001$, $\eta_p^2 = .580$, indicating that response times were faster during congruent trials (297.43 ± 105.74 ms) compared to incongruent trials (315.08 ± 104.49 ms). A significant interaction was not evident between Task and Condition, $F(1,15) = 3.630$, $p = .076$, $\eta_p^2 = .195$.

For the mTBI beyond 12 months group there was a significant main effect of Task, $F(1,23) = 21.189$, $p < .001$, $\eta_p^2 = .586$, indicating that response times were faster during the global task (280.73 ± 123.40 ms) compared to the local task (426.32 ± 100.08 ms). There was also a significant main effect of Condition, $F(1,23) = 166.461$, $p < .001$, $\eta_p^2 = .917$, indicating that response times were faster during the congruent trials (331.31 ± 105.74 ms) compared to incongruent trials (375.75 ± 104.48 ms). Additionally, there was a significant interaction between Task and Condition, $F(1,23) = 11.858$, $p = .004$, $\eta_p^2 = .442$, indicating the same global processing bias that was observed for the control group. That is, response times were faster during the local task for congruent letters (383.89 ± 99.12 ms) compared to incongruent letters (468.75 ± 119.97 ms), $t(23) = -6.445$, $p < .001$, but not during the global task for congruent letters (278.72 ± 137.51 ms) compared to incongruent letters (282.74 ± 125.97 ms), $t(23) = -0.237$, $p = .816$.

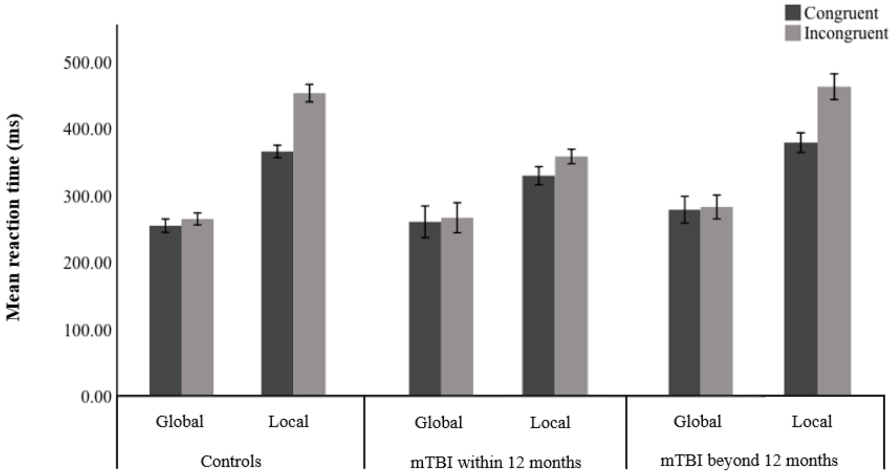


Figure 7. Mean reaction times in each group as a function of congruency (congruent/incongruent) and task (global/local). Error bars indicate ±1 SE of the mean.

3.4.2 Accuracy

Figure 8 displays mean response accuracy (percentage) in each group as a function of task (global/local) and letter congruency (congruent/incongruent). Significant main effects were observed for Task, $F(1,53) = 10.155$, $p = .002$, $\eta_p^2 = .161$, Condition, $F(1,53) = 60.210$, $p < .001$, $\eta_p^2 = .532$, and Group, $F(1,53) = 3.246$, $p = .047$, $\eta_p^2 = .109$. There was an interaction between Task and Group, $F(2, 53) = 22.553$, $p < .001$, $\eta_p^2 = .460$, between Condition and Group $F(2,53) = 8.709$, $p = .001$, $\eta_p^2 = .247$, and between Task and Condition, $F(1,53) = 5.647$, $p = .021$, $\eta_p^2 = .096$. Additionally, there was an interaction between Task, Condition and Group, $F(1,53) = 3.481$, $p = .038$, $\eta_p^2 = .116$. To investigate the three-way interaction, two-way ANOVAs were conducted separately for each group, with Task and Condition as within-subject factors.

For the control group, there was a significant main effect of Task, $F(1,23) = 35.520$, $p < .001$, $\eta_p^2 = .607$, indicating that accuracy scores were higher during the global task (97.04 ± 4.72 %) compared to the local task (92.09 ± 5.02 %). There was also a significant main effect of Condition, $F(1,23) = 70.572$, $p < .001$, $\eta_p^2 =$

.754, indicating that accuracy scores were higher during congruent trials (98.25 ± 3.82 %) compared to incongruent trials (90.88 ± 5.85 %). Additionally, there was a significant interaction between Task and Condition, $F(1,23) = 16.724$, $p < .001$, $\eta_p^2 = .421$, indicating that accuracy scores were lower during the local task for incongruent letters (86.81 ± 8.96 %) compared to congruent letters (97.38 ± 5.14 %), $t(23) = 7.451$, $p < .001$, similarly, accuracy scores were lower during the global task for incongruent letters (94.96 ± 6.69 %) compared to the congruent letters (99.13 ± 6.01 %), $t(23) = 6.749$, $p < .001$.

For the mTBI within 12 months group, there was a significant main effect of Task, $F(1,15) = 10.291$, $p = .006$, $\eta_p^2 = .407$, indicating that accuracy scores were higher during the local task (97.52 ± 6.14 %) compared to the global task (93.62 ± 5.78 %). There was no significant main effect of Condition, $F(1,15) = 1.242$, $p = .283$, $\eta_p^2 = .076$), and no significant interaction between Task and Condition, $F(1,15) = 0.228$, $p = .640$, $\eta_p^2 = .015$). In sum, a reduced global processing bias was found, with no congruency effect.

For the mTBI beyond 12 months group, there was a significant main effect of Task, $F(1,15) = 18.030$, $p = .001$, $\eta_p^2 = .546$, indicating that accuracy scores were higher during the global task (95.83 ± 5.78 %) compared to the local task (91.15 ± 6.14 %). There was also a significant main effect of Condition $F(1,15) = 23.037$, $p < .001$, $\eta_p^2 = .606$, indicating that accuracy scores were higher during congruent trials (96.35 ± 4.68 %) compared to incongruent trials (90.63 ± 7.17 %). A significant interaction was not evident between Task and Condition, $F(1,15) = 1.478$, $p = .243$, $\eta_p^2 = .090$.

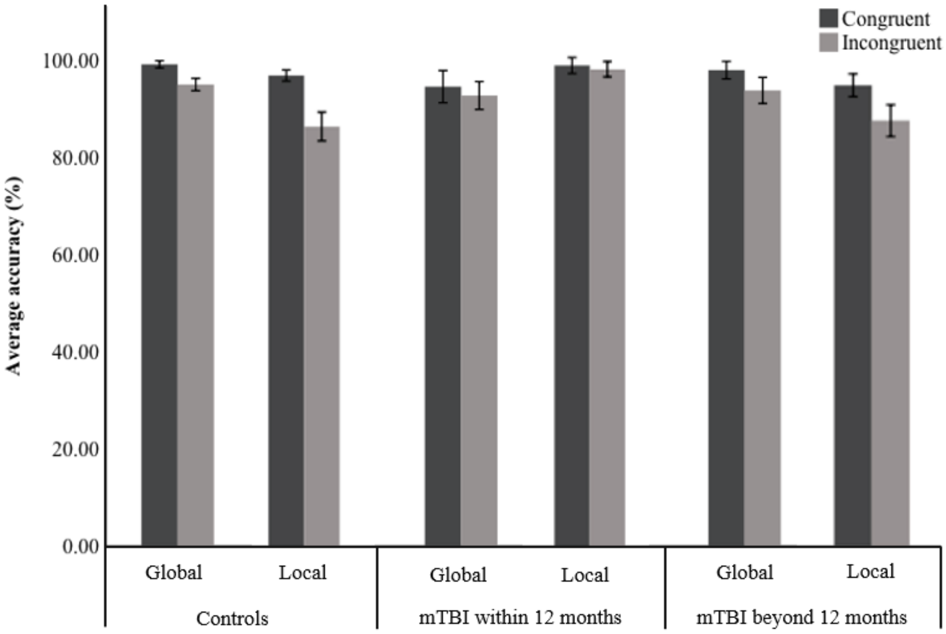


Figure 8. Mean accuracy scores in each group as a function of congruency (congruent/incongruent and task (global/local). Error bars indicate ±1 SE of the mean.

3.5 Discussion

Participants with no history of mTBI showed a global processing bias, whereas people with a recent history of mTBI (within the last 12 months) showed reduced global processing bias. That is congruency differences were not evident when processing global compared to local dimensions. Individuals who sustained their most recent mTBI more than one year earlier displayed the same global processing bias that healthy control participants displayed. It is widely reported that neuroplasticity after mTBI (depending on severity of injury) requires about one year to partially restore both structural and functional networks (Dall'Acqua et al., 2017; Jia et al., 2021). Thus, performance comparable to control participants may reflect general restoration of functional and structural networks in the affected brain regions of participants who sustained an mTBI more than one year earlier. This finding further suggests that global processing abilities may return to normal levels by one year after the injury.

In addition, individuals with a recent history of mTBI had fewer correct responses across both congruency types during the global task compared to the local task. This may reflect a bias towards processing local information, which is consistent with the findings of Chapter 2, who reported that people with mTBI were less susceptible to visual illusions than healthy controls, and thus were more accurate at making relative size judgments. The authors argued that the more accurate size judgments in people with mTBI may derive from their tendency to prioritize the analysis of local details in visual processing of multiple objects. This notion is consistent with the findings of Alnawmasi et al. (2019), who used glass patterns (i.e., visual stimuli made of multiple pairs of dots, that give the percept of a specific form) to assess how people with mTBI integrate spatially distributed stimuli into a coherent pattern. The authors found that people with mTBI displayed an impaired ability to discriminate between glass patterns. Given that the task required attention to the global (the glass pattern) rather than the local (the dots) features, Alnawmasi et al. (2019) speculated that increased attention to local information might have disrupted attention to the "bigger picture", which may have impacted object recognition abilities. Accordingly, our findings provide additional evidence in support of reduced global processing bias in people with a recent history of mTBI.

The results of our study may also provide an explanation for the additional impairments that are commonly observed in people with mTBI. For instance, people with a history of mTBI have been found to display deficits in social information processing (e.g., emotion perception), which is thought to be a function of poor facial affect recognition (Neumann et al., 2016). Previous research has consistently demonstrated that most individuals process faces holistically, integrating different facial features into a unified representation rather than analyzing individual features in isolation (Richler, Cheung, & Gauthier, 2011; Zhao, Bülthoff & Bülthoff , 2016). This holistic processing allows individuals to perceive the overall emotional expression conveyed by a face (Vrancken, Germey, & Verfaillie, 2017). However, when there is a reduced global processing bias, individuals may struggle to accurately perceive and interpret facial expressions. This is because reduced global processing bias impairs the ability to process faces holistically, making it difficult to integrate individual features of face into a unified whole (Cenac et al., 2019; Gold, Mundy, & Tjan, 2012). Therefore, the reduced global processing bias observed in the present study may help explain the facial affect recognition deficits observed in people with a history of mTBI, potentially shedding light on the underlying mechanisms of social information processing impairments in this population.

In addition to addressing social deficits, our findings may also inform understanding of the impact of deficient global processing on everyday tasks in a constantly changing environment. While research on visuospatial information processing in mTBI is limited, studies using simulated driving tasks have shown that people with mTBI sometimes have difficulty processing information that is important for safe and efficient driving, such as rapid and accurate processing of multiple inputs, and anticipation of road hazards (Milleville-Pennel et al., 2010; Preece et al., 2011). Given that individuals with a recent history of mTBI may have reduced ability to engage in global processing, it is possible that their ability to perceive and respond to dynamic visual information while driving (e.g., road signs, traffic lights, and other vehicles) is disrupted. Research on hazard detection in expert and novice drivers suggests an association between holistic processing and the ability to detect hazards quickly and accurately (Wolfe et al., 2017). Expert drivers tend to scan their driving environment more constantly; this enables them to integrate multiple inputs from across the visual field, which allows for faster identification of hazards in comparison to novices (Wolfe et al., 2020).

A number of limitations of the current study warrant discussion. First, the reliance on self-report rather than a medical diagnosis to establish the occurrence of mTBI raises potential concerns. Self-reporting introduces the possibility for recall bias, which can impact the accuracy of reported information. That is, people with mTBI may have difficulty accurately recalling the details of their injury, including the details surrounding the event (i..e, how the injury occurred, duration of loss of consciousness) and the severity of symptoms. This can be influenced by various factors, such as the passage of time since injury, emotional distress, and cognitive impairments associated with the injury itself. Second, the design of our study, which was conducted online and in a cross-sectional manner, imposed limitations on our ability to assess individuals immediately after experiencing an mTBI. Consequently, we were unable to establish a causal relationship between mTBI history and the observed reduction in global processing bias. It is crucial to acknowledge this limitation, as our findings may not fully capture the acute stages of mTBI. To overcome this limitation, we recommend conducting a longitudinal study that tracks the changes in global processing bias as people recover from an mTBI.

Future studies should use neuroimaging techniques, such as functional magnetic resonance imaging (fMRI) or electroencephalography (EEG), to investigate the neural mechanisms underlying reduced global processing bias in individuals with a recent history of mTBI. Additionally, utilizing eye-tracking technology could be valuable in identifying whether individuals with mTBI exhibit atypical visual attention towards objects, potentially providing insight on how they process visual information within their environment.

Chapter 4

Experiment 3: Propensity for movement specific reinvestment and mild traumatic brain injury[9]

4.1 Abstract

Mild traumatic brain injury (mTBI) represents a complex pathophysiological outcome of biomechanical forces on the brain, often resulting in a variety of cognitive, perceptual, and motor impairments. Following injury or accident, people with mTBI are likely to be concerned about preventing pain or re-injury, so we asked whether they have a greater propensity to consciously monitor and control their movements. We also examined whether an association exists between the propensity to consciously monitor and control movements and various mTBI clinical factors (e.g., time since most recent mTBI, number of mTBI, symptom severity). One hundred fifty-seven participants with mTBI and one hundred eighty-eight controls completed the Movement Specific Reinvestment Scale (MSRS), which was used as measure of the propensity for conscious monitoring and control of movements (i.e., movement specific reinvestment). Multiple regression analyses were conducted to examine the relationship between movement specific reinvestment and mTBI clinical factors~~.~~ Compared with controls, people with mTBI had a greater propensity for movement specific reinvestment. Time since most recent mTBI was negatively associated with the conscious motor processing subscale of the MSRS. We speculate that during the early stages of recovery, people with mTBI may have a greater tendency to consciously control their movements to avoid pain, re-injury, or trauma. Further understanding of the relationship between conscious motor processes and mTBI may be instrumental for tailoring rehabilitation strategies to meet the individual needs of the person with mTBI.

[9] Based on: **Sidhu, A.**, Uiga, L., Langley, B., Draper, N., & Masters, R.S.W. (2024). Movement specific reinvestment and mild traumatic brain injury. *International Journal of Sport and Exercise Psychology (Special Issue, Mind in Action)*

4.2 Introduction

Approximately 42 million people globally are affected by mild traumatic brain injury (mTBI) each year (Van Pelt et al., 2019). mTBI results from complex pathophysiological processes that occur when aberrant biomechanical forces are applied to the brain. These forces can cause a range of cognitive, perceptual, and motor impairments. It is well established that mTBI can lead to altered movement patterns and increased risk of musculoskeletal injury (McPherson et al., 2019); however, research into motor impairments following mTBI has primarily focused on neurophysiological factors (e.g., motor cortex excitability) that contribute to motor control complications (De Beaumont et al., 2011), with little attention given to psychological factors.

Following injury, people without mTBI often display guarded movements. Psychological factors, such as fear or anxiety about movement-related pain or re-injury are the likely cause (Nishi et al., 2019; Vlaeyen et al., 1995). Evidence suggests that in such cases, people may use conscious motor processing to control the mechanics of their movements in order to prevent pain or re-injury, or both (e.g., Ellmers et al., 2021; Selfe et al., 2015). It has been reported that people also display guarded movements following mTBI and alter their movement patterns to limit the exacerbation of mTBI-specific symptoms and/or prevent reinjury (e.g., Fino et al., 2018; Martini et al., 2021). However, to our knowledge, the association between conscious motor processing and mTBI has not been investigated. Insights into this relationship could provide opportunities to optimize rehabilitation outcomes or reduce likelihood of further brain injury.

A significant challenge for researchers is to characterize and assess conscious motor processing. One approach, the theory of reinvestment (Masters, 1992; Masters & Maxwell, 2008; Masters, Polman, & Hammond, 1993), proposes that the propensity to become consciously engaged in moving is a function of individual differences in personality (Masters & Maxwell, 2008; Masters, Polman, & Hammond, 1993). Masters, Eves, and Maxwell (2005) developed a Movement Specific Reinvestment Scale (MSRS), which is thought to assess dimensions of movement control that are associated with the tendency to consciously attend to and control movements (Conscious Motor Processing, CMP) and the tendency to be self-consciousness about presentation when moving (Movement Self-Consciousness, MS-C).

Studies using the MSRS suggest that high scores are associated with greater fall-related anxiety in older people (Young et al., 2016), and an increased incidence of falling by older people (Musculus et al., 2021; Wong et al., 2008). High scores have also been reported to be associated with greater functional impairment following stroke (Orrell, Masters, & Eves, 2009), longer duration of Parkinson's disease (Masters et al., 2007), and poorer motor performance under psychological pressure in sports (Jackson, Ashford, & Norsworthy, 2006; Masters, Polman, & Hammond, 1993; Maxwell, Masters, & Poolton, 2006). Selfe et al. (2015) also reported that people who reported more self-reported knee pain scored higher on the scale. The authors further suggested that the propensity for conscious involvement in movement may play a role in the way an individual responds to pain (e.g., more guarded movements). These findings give credence to the possibility that following an mTBI, individuals have a greater propensity to consciously monitor and/or control their movements in an attempt to prevent pain or re-injury.

Consequently, we sought to increase understanding of the role of conscious motor processes in mTBI by comparing MSRS of people with mTBI and people without mTBI (age-matched controls), and by investigating the relationship between mTBI clinical factors (number of mTBI, time since most recent mTBI and symptom severity) and movement specific reinvestment. We were also interested in examining sex differences in the relationship between conscious movement processes and mTBI. There is a growing body of research examining sex differences in functional outcomes post mTBI, with females demonstrating higher anxiety, greater fatigue, and impaired gait (e.g., Howell et al., 2017), as well as longer recovery times (Aggarwal et al., 2020). Hence, we investigated whether sex differences existed in the propensity for movement specific reinvestment in people with and without a history of mTBI.

4.3 Methods

4.3.1 Participants

Participants were recruited to participate in this study using opportunistic convenience sampling via social media platforms (e.g., Facebook, Twitter) and university-based email lists of students and staff. To be included in the mTBI group, participants were required to self-report ≥1 head injury (see Section 2.2.1 for assessment of mTBI history). To be included in the control group, participants were required to self-report no significant head injury history. Individuals using psychoactive medications or with psychiatric conditions were excluded from the experiment. Of those who expressed an interest in participating in the study, 345 were eligible, including 157 people with mTBI (61 females, 96 males; mean age = 18.89 ± 1.39 and 188 non-injured controls (78 females, 110 males; mean age = 19.55 ± 4.18).

All participants had normal or corrected-to-normal vision. The experimental protocol was approved by the University's ethics committee and all participants provided informed consent electronically. Due to Covid-19, the study was conducted entirely online. Participants were advised that they were free to withdraw from the study at any time by closing the browser.

4.3.2 Measures

Demographic information (age, sex) and mTBI history were obtained from all participants. Participants were presented with an initial statement regarding mTBI: 'The following symptoms of a mild traumatic injury (mTBI), commonly known as concussion, after any impact are: felt drowsy, had a severe headache (way worse than any regular headache), felt pressure in your head, experienced nausea, had blurred or abnormal vision, couldn't tolerate bright light or noise, had ringing in your ears, were disorientated or confused, were uncoordinated or fell over or had balance problems, were "dinged" or had your "bell rung", felt like you were slowed down, "in a fog" or "didn't quite feel right", and were unconscious for any period of time'. Following this statement, participants were asked: 'have you ever had an mTBI or been told by a doctor that you had an mTBI?'. If participants responded yes, they were then asked to provide the following information regarding their injury: number of mTBI, time since most recent mTBI, and symptom severity.

4.3.3 Assessment of mTBI history

Detailed mTBI history was ascertained using the Ohio State University Traumatic Brain Injury Identification Method (OSU TBI-ID), a standardized procedure to elicit the lifetime history of traumatic brain injury (TBI) (Bogner & Corrigan, 2009; Corrigan & Bogner, 2007). The measure consists of 11 items that measure the presence of historical TBI, cause of TBI, length of loss of consciousness and age of first and last occurrence of loss of consciousness. Participants completed an online, self-administered version of the OSU TBI-ID, previously validated by Liquorice et al (2018). Additionally, to quantify the presence of self-reported symptoms, participants with a history of mTBI completed the Rivermead Post Concussion questionnaire (RPQ; 16 items, rated 0- not experienced at all to 4-severe problem, for a maximum score of 64).

4.3.4 Movement Specific Reinvestment

The primary outcome measure was the propensity for conscious monitoring and control of movements, which was assessed by the Movement Specific Reinvestment Scale (MSRS, Masters, Eves, & Maxwell, 2005; Masters & Maxwell, 2008). The MSRS, which has been reported to have good test-retest reliability and internal consistency (Laborde et al, 2015; Masters & Maxwell, 2008), consists of two sub-scales (5 items each) that are thought to reflect different dimensions of movement specific reinvestment. One dimension, Conscious Motor Processing (CMP), represents a person's tendency to consciously attend to and control their movements, whereas the other dimension, Movement Self-Consciousness (MS-C), represents a person's self-consciousness about how they present when they move. Responses to the MSRS are recorded using a 6-point Likert scale, with each item ranging from *strongly disagree* (1) *to strongly agree* (6). A maximum score of 60 points can be achieved on the MSRS, with higher scores indicating greater propensity for reinvestment of movements, and lower scores suggesting less propensity for reinvestment about movements.

4.3.5 Procedure

Participants opened an online link, which directed them to a participant information sheet containing all study information and an electronic consent form. After providing consent, all participants completed a demographics and mTBI history form. Participants who reported a history of mTBI subsequently completed standardized mTBI assessments via the OSU TBI-ID followed by the RPQ, after which they completed the MSRS. If a history of mTBI was not reported, participants completed only the MSRS. All measures were self-reported online (approximate duration to complete 10-15 minutes), using the Qualtrics survey platform.

4.3.6 Statistical analysis

A Group (mTBI, control) x Sub-scale (MS-C, CMP) x Sex (females, males) multivariate analysis of variance was used to examine differences between mTBI participants and controls, and males and females as a function of the separate sub-scales of the MSRS. Where appropriate, follow-up tests were conducted using Bonferroni corrected independent samples t-tests (two-tailed). Values of $p < 0.05$ were assumed to be statistically significant.

Multiple regression analyses were calculated separately for MS-C and CMP (dependent variables), using time since most recent mTBI, symptom severity, number of mTBI, age, and sex as independent (predictor) variables. The regression model was tested for multicolloinearity using the variance inflation factor (VIF). The variance inflation factors for all of the variables were less than 10, which indicates no evidence of multicollinearity (Kleinbaum et al., 1988).

4.4 Results

4.4.1 Movement specific reinvestment

Group (mTBI, control) x Sub-scale (MS-C, CMP) x Sex (females, males) analysis revealed a main effect of Sub-scale, Wilks's lambda = 0.805, $F(1, 341) = 82.377$, $p < .001$, $\eta_p^2 = .195$. There was no significant three way interaction, Wilks's lambda = 1.00, $F(1, 341) = 0.158$, $p = .692$, $\eta_p^2 = .000$; however, significant two-way interactions were evident for Group x Sub-scale, Wilks's lambda = .947, $F(1, 341) = 19.154$, $p < .001$, $\eta_p^2 = .053$, and Sex x Sub-scale, Wilks's lambda = .960, $F(1, 341) = 14.312$, $p < .001$, $\eta_p^2 = .040$. The test of between-subject effects indicated that there was also a significant main effect of Group, $F(1, 341) = 339.035$, $p < .001$, $\eta_p^2 = .499$, but not of Sex, $F(1, 341) = 2.754$, $p = .098$, $\eta_p^2 = .008$, and no Sex x Group interaction, $F(2, 343) = 3.689$, $p = .056$, $\eta_p^2 = .011$.

The significant Group x Sub-scale interaction (see Figure 9) was followed up by separate independent samples t-tests for each sub-scale (CMP, MS-C). People with mTBI had higher CMP scores (M = 21.80, SD = 3.49) compared to controls (M = 13.40, SD = 4.62), $e(343) = -18.755$, $p < .001$ (after Bonferroni correction for 2 comparisons). Similarly, people with mTBI had higher MS-C scores (M = 18.29, SD = 4.73) compared to controls (M = 12.12, SD = 4.29), $t(343) = -12.707$, $p < .001$. Differences between mTBI and control were greater for scores on the CMP sub-scale than the MS-C sub-scale ($t(343) = 4.568$, $p < .001$) (see Figure 8).

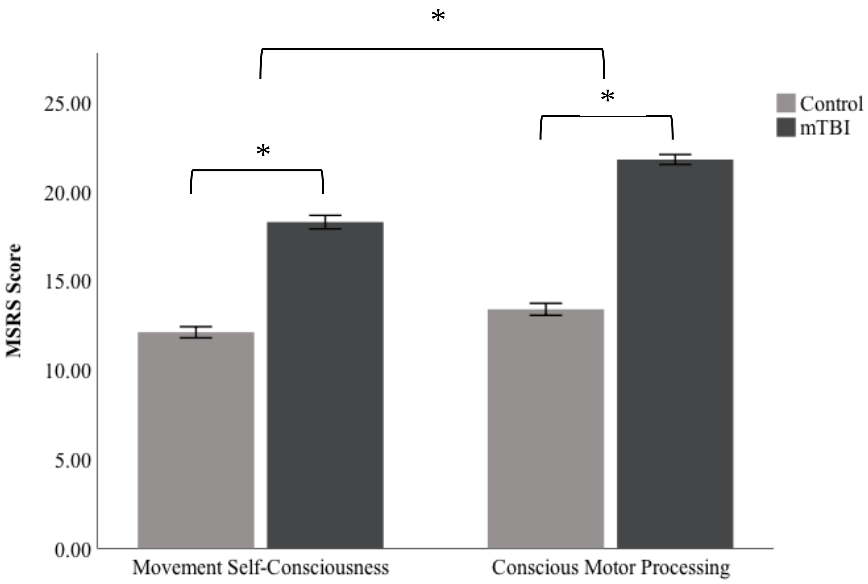


Figure 9. Mean scores on the Movement Self-Consciousness sub-scale and the Conscious Motor Processing sub-scale of the Movement Specific Reinvestment Scale (MSRS) for mTBI participants and controls. * indicates p < .001 level of significance.

The Sex x Sub-scale interaction (see Figure 10) was also followed up by separate independent samples t-tests for each sub-scale (CMP, MS-C). The results revealed that females had higher MS-C scores (M= 15.73, SD = 5.53) than males (M = 14.38, SD = 5.33), $t(343) = 2.253$, $p = .025$; however, there was no difference in CMP scores between females (M = 16.89, SD = 5.92) and males (M = 17.45, SD = 5.86), $t(343) = -0.847$, p = . 398.

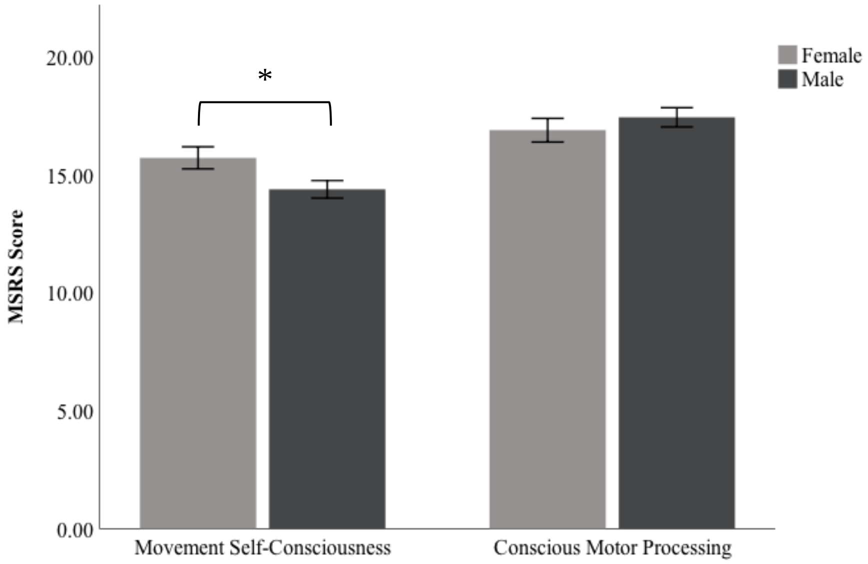


Figure 10. Mean scores on the Movement Self-Consciousness sub-scale and the Conscious Motor Processing sub-scale of the Movement Specific Reinvestment Scale (MSRS) for female and male participants. * indicates p < .05 level of significance.

4.4.2 Multiple regression analysis

Hierarchical regression analyses were conducted separately to predict MS-C score and CMP score (see Table 1). For each analysis, independent (predictor) variables were added to the equation in two steps. In Step 1, age and sex were included as control variables to account for their potential confounding effects. In Step 2, the number of mTBI(s), time since the most recent mTBI, and symptom severity were added to assess the unique contribution of these mTBI-specific factors.

The final models explained 9.3% of the variance in MS-C scores, and 9.7% of the variance in CMP scores. The only significant predictor of MS-C scores was sex. However, time since most recent mTBI (β = -0.278; p = .002) made a unique contribution to variance in CMP scores, with a significant negative beta weight indicating that more recent mTBI was associated with higher scores on the sub-scale. Age, number of mTBI, and symptom severity did not contribute significantly to the model.

Table 1. Summary of hierarchical regression analyses for variables predicting Movement Self-Consciousness and Conscious Motor Processing

	Movement Self-Consciousness				Conscious Motor Processing			
Variable	R^2	B	SE	β Weight	R^2	B	SE	β Weight
Step 1	0.073*				0.013			
Age		-0.171	0.246	-0.054		-0.221	0.188	0.095
Gender		-2.586	0.755	-0.267*		-0.457	0.577	-0.064
Step 2	0.093*				0.312*			
Age		-0.028	0.260	-0.009		0.008	0.192	0.004
Gender		-2.381	0.784	-0.246*		-0.065	0.579	-0.009
Number of mTBI		-0.009	0.296	-0.003		0.127	0.219	0.049
Time since most recent mTBI (years)		-0.226	0.133	-0.148		-0.314	0.098	-0.278*
Symptom Severity		0.002	0.032	0.005		0.011	0.023	0.040

* indicates $p < .05$ level of significance.

4.5 Discussion

The present study supports the prediction that people with mTBI have a greater propensity for movement specific reinvestment than similar aged people without mTBI (controls). While people with mTBI scored significantly higher than controls on both sub-scales of the MSRS, they had relatively higher scores than controls for conscious motor processing compared to movement self-consciousness. In addition, we found conscious motor processing to be negatively associated with time since most recent mTBI, suggesting that the propensity to consciously control movements tends to decrease over time following injury.

Our findings align with literature suggesting that conscious motor processing plays a more prominent role than movement self-consciousness in motor control by people with movement-related problems (e.g., Masters et al., 2007; Orrell, Masters, & Eves, 2009; Wong et al, 2008). Consequently, during the early stages of mTBI injury, people may have a greater tendency to consciously monitor and control their movements in order to avoid pain, re-injury, or trauma. Given that people with mTBI often report high levels of fear of re-injury (Anderson et al., 2019; Moss & Slobounov, 2006; Reinking et al., 2022), it is likely that in an attempt to prevent further incidents, they consciously control their movements. Indeed, partial support for this speculation can be found in the fact that the propensity for movement specific reinvestment has been linked to fear and anxiety, and that people who are anxious about falling often consciously process their movements in an attempt to avoid falling (e.g., Ellmers et al., 2020; Ellmers, Cocks, & Young, 2020; Wong et al., 2008). However, future work will need to establish the degree to which movements in people with mTBI are affected by conscious motor processing in anxiety provoking situations.

Time since injury was negatively associated with conscious motor processing. People with mTBI are often advised to gradually resume their cognitive and physical activities to avoid exacerbation of symptoms and facilitate recovery (Marshall et al., 2012; Schneider et al., 2017; Silverberg et al., 2020). As a result, it is probable that they learn to use conscious motor processing as an explicit attention strategy because consciously controlling the mechanics of their actions may be the most effective way to adapt to pain or anticipated pain. In addition, mTBI can cause alterations in brain structure and function, which can lead to compromised neural efficiency necessitating alterations in typical task related recruitment patterns to maintain performance (Urban et al., 2021). However, over time, as the brain recovers, neural plasticity may contribute to the restoration of cognitive, perceptual, and motor functions (Dall'Acqua et al., 2017), and potentially reduce the need to consciously control movements. Longitudinal designs are needed to elucidate the underlying mechanisms governing the reduction in conscious monitoring and control of movements over time following an mTBI.

Regardless of mTBI history, females scored higher on the movement self-consciousness sub-scale. Research suggests that females demonstrate greater self-awareness than males (Smee et al., 2017), potentially due to societal pressures and expectations to move in a certain way (Lunde & Gattario, 2017). Our study is the first to demonstrate sex differences in the level of movement self-consciousness in mTBI, so further research is necessary to understand the exact underpinnings of this finding.

Although this study adds a new dimension to our understanding of reinvestment in mTBI, the findings should be interpreted with caution. The study used a trait measure of movement specific reinvestment, so it does not reflect real-time consciousness of movement execution. Given that mTBI leads to disruption in neuronal function, future studies should adopt more objective measures to examine whether people with mTBI display unique neural signatures of movement specific reinvestment. The utilization of electroencephalography (EEG) coactivation between the verbal-analytical (T3) and the frontal motor planning (FZ) regions of the brain while performing a motor skill may provide a departure point for this. Specifically, it has been argued that greater co-activation between these two regions of the brain is as an objective indicator of conscious control of movement (Zhu et al., 2011). However, it is important to note that this argument is currently under debate (Parr et al., 2020).

A limitation was that mTBI history was self-reported and, therefore, participants may have been unable to accurately recall the details of their prior mTBI (i.e., date mTBI was sustained, severity of mTBI, number of mTBI). As a result, participants may have under- or over-reported their mTBI history. The study is also cross-sectional, so causality between mTBI and movement specific reinvestment cannot be determined. Given that this was an online study, we were unable to administer the MSRS questionnaire to participants directly after sustaining a mTBI. Further studies, including longitudinal follow-up studies, are needed to investigate the relationship between reinvestment and people with mTBI from the time of injury throughout and beyond clinical recovery.

Nevertheless, the findings from this study could have public health implications. Research suggests that individuals with a prior history of mTBI are at an increased risk of sustaining a repeat mTBI (Guskiewicz et al., 2003; Zemper, 2003). Furthermore, it has been observed that these recurrent mTBIs often occur via the same mechanism that caused the initial injury (Theadom et al., 2015). Given that movement specific reinvestment, specifically conscious motor processing, has the power to predict future error prone movements (Musculus et al., 2021), future research should aim to investigate whether increased propensity to consciously process movements predicts the likelihood of future injuries in people with mTBI, a factor that may carry significant implications for reducing the risk of a repeated mTBI and/or musculoskeletal injury.

Chapter 5

Experiment 4: Anticipation of deceptive and non-deceptive movements in club rugby players with a history of mild traumatic brain injury[10]

5.1 Abstract

Expert athletes tend to use a global processing strategy when anticipating an opponent's movements. The findings from Chapter 2 and 3 suggested a reduced global processing bias following mild traumatic brain injury (mTBI). Experiment 4, therefore, sought to investigate the potential impact of mTBI on the ability to anticipate both deceptive and non-deceptive movements. Club rugby players with a history of mTBI (N=16) and without a history of mTBI (N=16) anticipated the final running direction of an opponent changing direction. Our results showed that club rugby players with a history of mTBI took significantly longer to respond compared to club rugby players without history of mTBI and were significantly more accurate than club rugby players without a history of mTBI when anticipating deceptive and non-deceptive movements.

[10] **Sidhu, A.,** Uiga, L., Langley, B., & Masters, R.S.W. (under review). Anticipation of deceptive and non-deceptive movements in club rugby players with a history of mild traumatic brain injury. *The Journal of Sport and Exercise Science*

5.2 Introduction

Mild traumatic brain injury (mTBI) is a common occurrence in high-impact sports and can result in significant impairments in cognitive and motor functions. It is well-established that cognitive deficits can occur in attention, working memory, and executive functions (McCrory et al., 2017). However, there is limited research on the effects of mTBI on perceptual-cognitive abilities, particularly visual anticipation.

Visual anticipation is defined as the capability of an individual to use information from their environment to predict forthcoming events and execute appropriate actions (Broadbent, Causer, Ford, & Williams, 2015). Visual anticipation is crucial for successful performance, particularly in contact sports, where quick decisions and reactions are necessary to avoid injury. Research into applied motor behavior has most commonly relied on the expert–novice paradigm to identify the perceptual-cognitive characteristics of experts; this research has established that skilled athletes are better at extracting meaningful contextual information (i.e., visual cues from an opponent) from the dynamic visual scene, which is reflected by better anticipation and decision-making skills (Huys et al., 2008; Williams, Ward, & Smeeton, 2004). That is, expert performers possess superior ability to allocate their attention to perceptual cues that are relevant for the task at hand, while effectively ignoring irrelevant cues (Mann et al., 2007). It is argued that this superior ability results from the capacity to effectively utilize multiple sources of motion information from all parts of an opponent's body (Savelsbergh et al., 2005). Novice performers, on the other hand, tend to rely more on single sources of motion information from body segments to anticipate their opponent's moves (Williams & Ericsson, 2005). These disparities in attentional distribution between experts and novices could potentially be attributed to differences in how motion stimuli are processed. That is, novices may process information more locally, whereas experts may process information more globally.

Global processing refers to attending to the overall structure of a stimulus, while local processing involves focusing on specific details or individual components of a stimulus. Research using the spatial occlusion paradigm (i.e., hiding visual information that is normally available at specific spatial areas/body segments) has suggested that expert performers rely on a more global pickup strategy during a one-on-one situation, allowing them to process visual information from several areas of the body (Huy et al., 2009). Conversely, novice performers rely more on ‘local’ information conveyed in single cues (Huys et al., 2008; Huys, et al., 2009; Jackson et al., 2018). For example, Huys et al. (2009) manipulated stick figure images of tennis players performing a tennis shot by spatially occluding movement patterns associated with regions across the body (e.g., local information from the arm and racket was occluded). The authors found that when information pertaining to the arm and the racket was occluded, anticipation performance deteriorated significantly for both experts and novices; however, only experts showed a significant decrease in performance when the hips, trunks, and legs were occluded. These findings suggest that experts employ a more global than local perceptual strategy.

Abernethy, Zawi, and Jackson (2008) also argued that experts tend to initially direct their visual attention towards more proximal body parts, such as the trunk, and later shift their attention towards more distal parts, such as the arm and wrist, as the movement progresses. Although the information sources relied upon vary between sports, experts have generally been shown to pick up earlier-arising cues from more proximal information sources, such as the hips in football (Causer et al., 2017) or the trunk in fencing (Hagemann et al., 2010). Less-skilled athletes rely more on later-occurring, more distal information (e.g., the foot in football or the arm in fencing). This notion has also been supported by Williams, Huys, Cañal-Bruland, and Hagemann (2009) who reported that skilled athletes were affected by the manipulation of information in proximal and distal regions, whereas less-skilled athletes were only affected by manipulations of information in the distal regions; further suggesting that skilled performers pick up information in a more distributed, global and continuous manner, rather than relying exclusively on the serial processing of a single or local source of information.

The impact of mTBI on visual anticipation skills has yet to be explored. However, the work conducted in Chapter 2 and 3 suggests that people with a history of mTBI may exhibit deficits in integrating visual information. Notably, in Chapter 2 we found that both the Ebbinghaus and the Müller-Lyer illusions were experienced less strongly by people with a history of mTBI compared to people without mTBI, resulting in more accurate size contrast judgments among people with mTBI. We concluded that this increased accuracy may be attributed to a tendency for people with mTBI to prioritize the analysis of local details (i.e., focus on individual elements and ignore the neighbouring visual information) in the visual processing of multiple objects. To further validate this assumption, in Chapter 3 we investigated global-local processing using the Navon task, which is a validated tool designed to measure responses to a visual scene both at the global level (grouped local elements, e.g., a forest) and the local level (individuated local elements, e.g., trees). In this task, participants were presented with a large letter (e.g., H or S) comprised of smaller letters (e.g., H or S). The stimulus was either congruent, in which the larger letter was constructed from the same smaller letters (e.g., a large H from small Hs), or incongruent, in which the larger letter was constructed from different smaller letters (e.g., a large H from small Ss). Participants were instructed to either identify only the larger letter (global task), or identify only the smaller letters (local task). Our findings revealed that people with a recent history of mTBI (within 12 months) demonstrated fewer correct responses in the global task compared to the local task, irrespective of congruency. This indicated that they did not display the typical global processing bias found in healthy individuals (i.e., an automatic tendency to attend to the overall structure of a stimuli first). Instead, they exhibited a greater inclination to focus on specific details within visual stimuli. Together, the findings from Chapters 2 and 3 suggest that people with a recent history of mTBI may show greater attention to specific aspects of a visual scene before attending to the overall structure. Consequently, this shift towards increased local processing in people with a recent history of mTBI may significantly affect their visual anticipation performance, as processing an individual source of visual information (i.e., focusing on only one body part or kinematic cue at a time) requires more time and effort than the simultaneous extraction of information across multiple body segments (global processing). Additionally, local processing may limit the ability to integrate information across a wider visual field, reducing the overall amount of information available for successful anticipation. A significant consequence of this is that people recovering from an mTBI may face challenges in detecting relevant cues necessary for anticipating opponent movements, which may predispose them to further injury (e.g., mTBI).

Thus, the aim of this study was to examine whether anticipatory performance differences exist between club rugby players with and without a history of mTBI. Rugby is a dynamic field-based sport characterized by sudden directional changes and high-impact collisions, requiring players to accurately anticipate and rapidly respond to the movements of attacking players. Given the high incidence of mTBI in club rugby (Rafferty et al., 2018), it is important to investigate whether skilled rugby players with a recent history of mTBI exhibit poorer anticipatory performance (e.g., slower response times, reduced accuracy) compared to players without a history of mTBI. Therefore, as a potential method for determining whether anticipation is impaired in rugby players following mTBI, we used a temporal occlusion paradigm to manipulate the availability of kinematic information and assess how players anticipate their opponents' movements with limited information. Club rugby players with and without a self-reported history of mTBI were required to anticipate the final running direction of players changing direction using a side-step (a deceptive movement to provide misleading kinematic information about their intentions) or using non-deceptive movements.

In Chapters 2 and 3 we showed that individuals with a recent history of mTBI utilize a local perceptual strategy. Consequently, they may face challenges in detecting relevant cues necessary for successful anticipation because locally processing individual sources of information generally takes longer and may therefore limit the amount of information picked up for anticipation. We hypothesized that individuals with a recent history of mTBI will demonstrate poorer response accuracy and slower response times than controls when anticipating movements.

5.3 Method

5.3.1 Participants

A priori power analysis using G∗Power 3.1 (Faul et al., 2009) determined that to achieve 95% power, alpha of 0.05, with expected effect size of 0.25 (Chapter 2), the required sample size was 28 participants. A mTBI group (N = 16) was formed of club rugby players with a history of mTBI within the last 12 months (7 females, 9 males; 21.35 ± 1.50 years), and a control group was formed of club rugby players without a known history of mTBI (14 females, 2 males; 22.63 ± 2.13 years).

To be included in the mTBI group, participants were required to self-report one or more incidents of head injury within the last 12 months (see below for assessment of mTBI history). To be included in the control group, participants were required to self-report no significant head injury history. Individuals who self-reported current use of psychoactive medications or psychiatric conditions (diagnosed or undiagnosed), were excluded from the experiment. All participants had normal or corrected-to-normal vision. The experimental protocol was approved by the University of Waikato Ethics Committee.

5.3.2 Assessment of mTBI history

To determine a detailed mTBI history, we utilized the Ohio State University Traumatic Brain Injury Identification Method (OSU TBI-ID), which follows a standardized procedure for collecting information on past TBI incidents (Bogner & Corrigan, 2009; Corrigan & Bogner, 2007). This assessment comprimises of 11 items that measure the cause of TBI, duration of loss of consciousness and age of first and last occurrence of loss of consciousness. Participants in this experiment completed an electronic version of the OSU TBI-ID, previously validated by Lequerica et al. (2018).

5.3.3 Test stimuli

Video clips representing a one-versus-one tackle scenario in rugby were taken from a previous study (Sherwood, Smith, & Masters, 2019). The clips consisted of both non-deceptive and deceptive trials (i.e., the attacking player utilized a side step to initiate a change in direction). The video clips were cut off at one of three time points relative to the final foot contact before change of direction: t1 (-100ms), t2 (0ms) and t3 (+100ms). Each clip started with a countdown sequence (3-2-1) and ended with a black screen that occluded the video and lasted for two seconds between trials. To indicate the start of a new trial, a tone was added in each video clip three seconds prior to the moment the foot makes its final contact before initiating a change in direction. The experiment comprised four blocks of 12 trials, containing six deceptive trials and six non-deceptive trials. Two deceptive and two non-deceptive trials were randomly occluded at each of the three time points. The practice block consisted of 10 randomly selected clips that included five deceptive trials and five non-deceptive trials. Participants completed at total of 48 trials.

5.3.4 Procedure

Prior to starting, demographic information (age, sex), rugby playing experience (number of years) and mTBI history were obtained from all participants. Participants who reported a history of mTBI were asked to provide the following information regarding their injury, including the number of mTBI, time since most recent mTBI, and symptom severity. Participants who reported a history of mTBI were also required to complete two questionnaires: the Ohio State University Traumatic Brain Injury Identification Method form and the Rivermead Post Concussion questionnaire.

In the test procedure, participants viewed each trial using a virtual reality (VR) headset (Oculus Quest 2). By using VR headsets to present 360° footage, participants are fully immersed in a virtual environment that replicates real-life situations, and can result in a high degree of ecological validity (Muhla et al., 2020; Slater & Wilbur, 1997). This level of immersion allows for a more engaging sensory experience, as participants can interact with the stimuli in a natural way.

To familiarize participants with the task, they first completed a practice block containing ten trials. The practice trials were then followed by the experimental task. Participants were instructed to anticipate the final running direction (left or right side) of the observed player as quickly and as accurately as possible. Participants reported their decision verbally, and were encouraged to stand in a position that they would typically adopt when defending. Following each block of trials, the VR headset was removed and participants rested for approximately 2 min before proceeding to the next block of trials. The experiment took 20 minutes to complete.

5.3.5 Data processing

Similar to Sherwood et al. (2019), response accuracy and time were computed for both deceptive and non-deceptive trials as a function of occlusion point (i.e., -100ms, 0ms, +100ms). Response time was calculated using the Audacity software (Version 2.3, Pennsylvania, USA), to determine the period of time elapsing between the onset of the tone and the onset of participants verbal response (i.e., indicating whether the player went left or right).

5.3.6 Statistical analysis

Statistical analyses were completed using SPSS (Version 24, IBM, UK). Three-way repeated measures Analyses of Variance (ANOVA) were conducted to examine response accuracy and reaction time separately, using within-subject factors of Stimuli Type (deceptive trials / non-deceptive trials) and Occlusion Point (100ms / 0ms / +100ms) and a between-subject factor of Group (mTBI history / control).[11]

[11] All participants with missing data were excluded from the analysis.

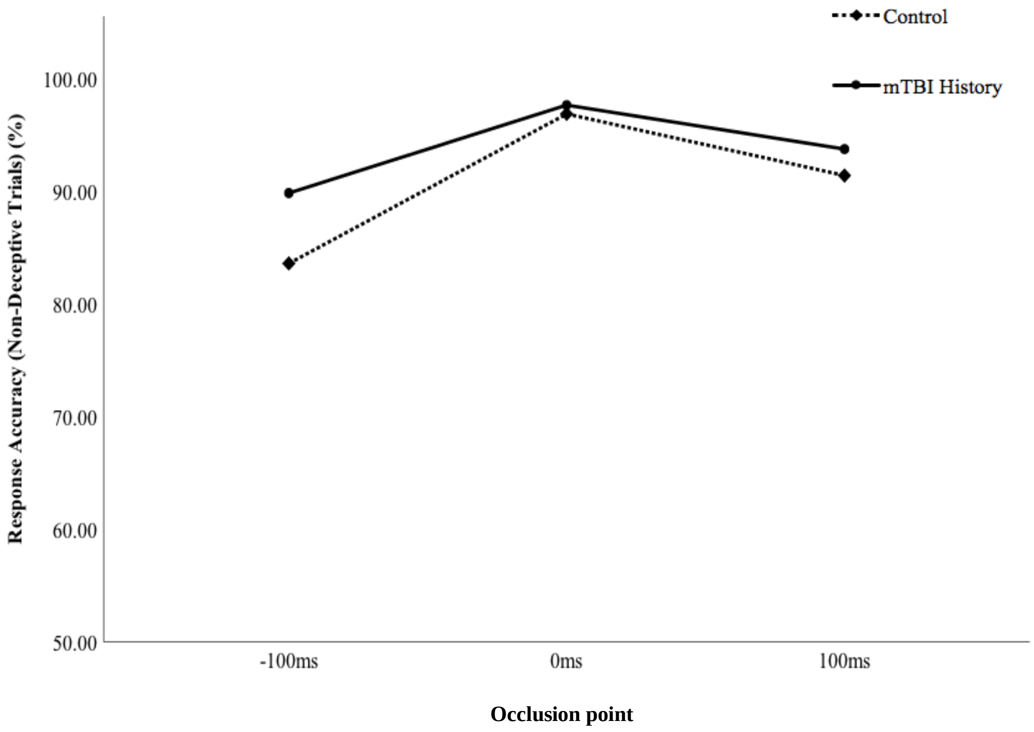
Follow-up analyses were conducted to further analyze significant interactions, using ANOVAs and Bonferroni corrected pairwise comparisons. Statistical significance was set at $p \leq 0.05$. Effect sizes were calculated as partial eta squared (η_p^2), with values of 0.01, 0.06 and 0.14 used to indicate small, medium and large effects sizes, respectively.

5.4 Results

5.4.1 Response accuracy

Response Accuracy during deceptive and non-deceptive trials is shown in Figure 11. A three-way interaction between Stimulus Type, Occlusion Point and Group was not found ($p > .05$); however, a significant two-way interaction was evident between Stimulus Type and Occlusion Point, $F(2,60) = 45.567$, $p < .001$, $\eta_p^2 = .608$. Follow-up analysis, using one-way ANOVA, revealed significant differences in response accuracy during non-deceptive trials as a function of Occlusion Point, $F(2,62) = 11.860$, $p < .001$. Bonferroni corrected pairwise comparisons showed that response accuracy improved significantly between -100ms and 0ms ($p < .001$), and decreased significantly between 0ms and +100ms ($p = .036$), but no significant difference was found between -100ms and +100ms ($p = .089$). One-way ANOVA also revealed that for deceptive trials there were significant differences in response accuracy as a function of Occlusion Point, $F(2,62) = 194.563$, $p < .001$). Bonferroni corrected pairwise comparisons, showed that response accuracy improved significantly between -100ms and 0ms, and -100ms and +100ms (*p's* < .001), but not significantly different between 0ms and +100ms ($p = 1.00$).

No other two-way interactions were evident (p's > .050), but main effects were evident for Stimulus Type, $F(1,30) = 42.193$, $p < .001$, $\eta_p^2 = .584$, Occlusion Point, $F(2,60) = 39.952$, $p < .001$, $\eta_p^2 = .847$, and Group, $F(1,30) = 4.501$, $p = .042$, $\eta_p^2 = .130$. Response accuracy was greater during non-deceptive trials compared to deceptive trials and for players with a history of mTBI compared to players without a history of mTBI. For Occlusion Point, Bonferroni corrected pairwise comparisons showed that response accuracy was significantly greater at +100ms and 0ms when compared to -100ms (p's < .001), but not significantly different between 0ms and +100ms ($p = .478$).



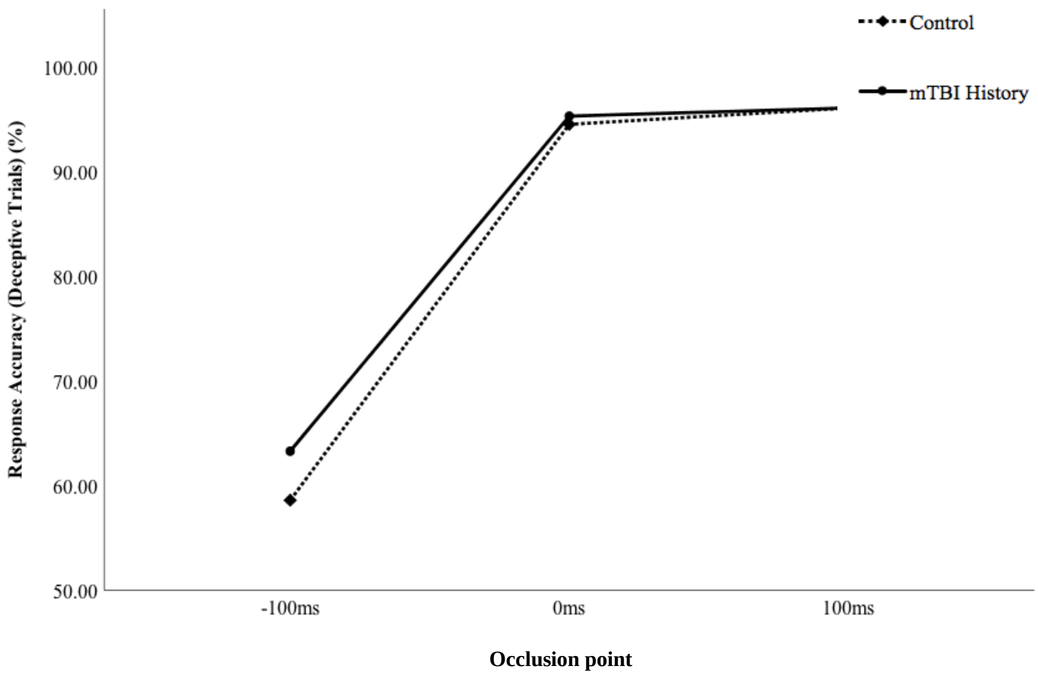


Figure 11. Mean response accuracy during non-deceptive trials (top) and deceptive trials (bottom) at each occlusion point.

5.4.2 Response times

Response Times for non-deceptive and deceptive trials are shown in Figure 12. A three-way interaction was evident between Stimulus Type, Occlusion Point and

Group, $F(2,60) = 3.671$, $p = .031$, $\eta_p^2 = .109$. To investigate the three-way interaction, two-way ANOVAs were conducted separately for each Stimulus Type.

For the non-deceptive trials, a significant two-way interaction was not evident between Occlusion Point and Group, $F(2,60) = 1.292$, $p = .282$, $\eta_p^2 = .041$. Main effects were evident for Occlusion Point, $F(2,60) = 22.443$, $p < .001$, $\eta_p^2 = .428$, and Group, $F(1,30) = 5.315$, $p = .028$, $\eta_p^2 = .150$. Bonferroni corrected pairwise comparisons showed that for Occlusion Point, response times were significantly slower at -100ms than 0ms trials ($p < 0.001$), and at 0ms than +100ms trials ($p < .001$), but not significantly different between +100ms and -100ms ($p = 1.00$). Players with a history of mTBI were significantly slower than players without a history of mTBI.

For deceptive trials, a medium to large effect size was evident, so it was concluded that a significant two-way interaction was present between Group and Occlusion Point, $F(2,60) = 3.115$, $p = .052$, $\eta_p^2 = .094$. A main effect was evident for Occlusion Point, F(2,60) = 31.961, $p < .001$, $\eta_p^2 = .516$, and, given the large effect size, it was also concluded that a main effect was evident for Group, $F(1,30) = 4.051$, $p = .053$, $\eta_p^2 = .119$. Follow-up analysis, using one-way ANOVA, revealed significant differences in response time for mTBI history group as a function of Occlusion Point, F(2,30) = 20.996, $p < .001$). Bonferroni corrected pairwise comparisons showed that response times increased significantly between -100ms and 0ms, and -100ms and +100ms (*p's* < .001), and decreased significantly between 0ms and +100ms ($p = .027$).

One-way ANOVA also revealed that for the control group there were significant differences in response times as a function of Occlusion Point, $F(2,30) = 11.797$, $p < .001$). Bonferroni corrected pairwise comparisons, showed that response time decreased significantly between -100ms and 0ms, and -100ms and +100ms (*p's* < .001), but was not significantly different between 0ms and +100ms ($p = .918$).

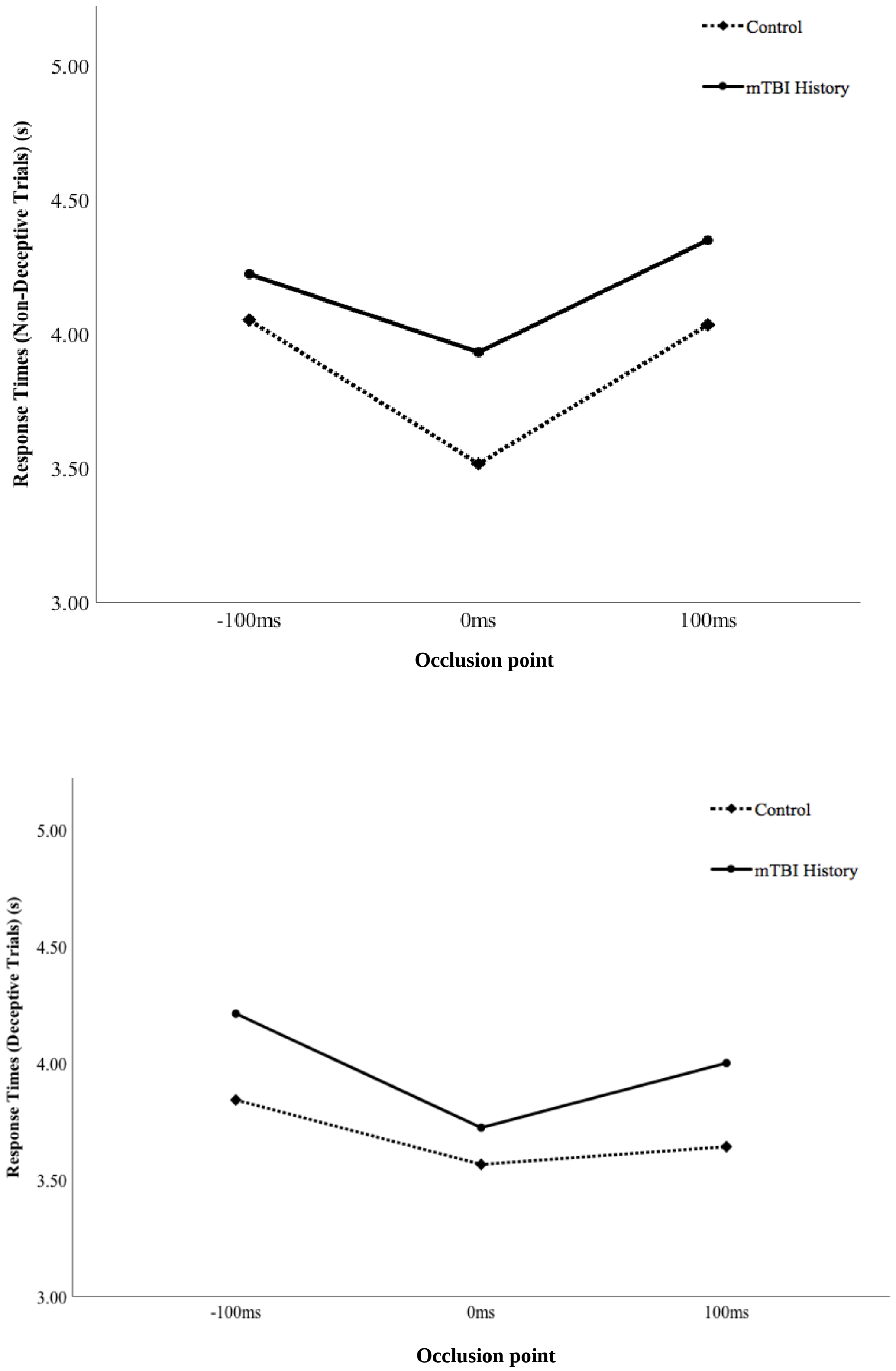


Figure 12. Mean response times during non-deceptive trials (top) and deceptive trials (bottom) at each occlusion point.

5.5 Discussion

The aim of this study was to investigate anticipatory performance in athletes with a history of mTBI. We hypothesized that individuals with a history of mTBI would demonstrate poorer response accuracy compared to individuals without a history of mTBI. However, our findings revealed the opposite effect, with individuals with a history of mTBI displaying significantly greater response accuracy than individuals without a history of mTBI during deceptive and non-deceptive trials. While this does not support our hypothesis, there are several factors that may have contributed to these findings. Given that all the participants in this study were experienced club rugby players, it is reasonable to assume that they had a high level of understanding when it came to perceiving and executing defensive actions. Extensive knowledge is likely to play a role in the ability to effectively comprehend the underlying kinematics that indicate movement outcomes, thus reducing erroneous judgements (Cañal-Bruland, van der Kamp, & van Kesteren, 2010). That is, expert players know which kinematic cues are most relevant when confronting an approaching opponent. The superiority observed in experienced players with a history of mTBI compared to experienced players without a history of mTBI may be a function of their bias towards local perceptual attention. The combination of domain specific knowledge and the inclination to focus locally on the details, may enable them to more effectively filter out irrelevant information and accurately extract the most reliable kinematic cue(s). As a result, they are able to anticipate outcomes more successfully. While this claim contradicts the prevailing narrative that expert players rely on integrating local information from different parts of the opponents' body to accurately anticipate movements, we speculate that following an mTBI expert players may exhibit a reduced ability to integrate local motion information into a coherent biological motion. As a result, they may have a reduced susceptibility to deceptive movements due to an impaired ability to group relevant and irrelevant kinematics cues together. This speculation is supported by our findings from Chapter 2, where it was argued that individuals with a history of mTBI were less susceptible to visual illusions due to their diminished ability to perceptually group visual stimuli based on proximity. Conversely, evidence suggests that healthy individuals typically find it more challenging to ignore distractors when those distractors are grouped with relevant cues (Blake & Shiffrar, 2007; Cutting & Kozlowski, 1977; Giese & Poggio, 2003; Thompson et al., 2005). Nonetheless, further research is warranted to directly examine how players integrate kinematic information following an mTBI to understand the mechanisms underlying their performance.

In both groups, response accuracy for deceptive and non-deceptive trials were observed to be highest when trials were occluded later. This finding may be due to the availability of more important cues in the later stages of a movement. Regardless, players with a history of mTBI were generally more accurate than players without a history of mTBI. This difference was particularly obvious before more information was available (-100ms). Since there was limited information available (-100ms) to process it could be speculated that experienced players with a history of mTBI were able to focus more effectively on early movement information that specifies the outcome of an action. Indeed, Brault et al. (2012) reported that experienced rugby players rely on information from their opponents' hips when anticipating their running direction. Thus, it is plausible to suggest that an increased tendency to prioritize local motion information may have enabled individuals with a history of mTBI to effectively focus on hip movements for successful anticipation. However, future work should investigate the visual search strategies employed by individuals with a history of mTBI to confirm this assumption.

Additionally, players with a history of mTBI took longer than controls to respond in both the non-deceptive trials and deceptive trials. This was expected, as it is widely reported that individuals with mTBI exhibit slower response times compared to controls, which can be attributed to the cognitive impairments that can occur following mTBI, such as difficulties with attention and information processing (Ozen & Fernandes, 2012). Furthermore, both players with a history of mTBI and controls were observed to respond slower in the deceptive trials during –100ms trials and +100ms trials. Studies have shown that experts who are skilled at detecting deception in movements rely on specific kinematic cues (i.e., subtle changes in action kinematics, limb displacement, and dynamics of movement signals) to accurately anticipate deceptive actions (Brault et al., 2012; Park et al., 2019; Tidoni et al., 2013). As a result, experts tend to wait longer before initiating their movements in order to gather more information that informs their anticipation, resulting in fewer errors (Brault et al., 2012). Furthermore, research has shown that local processing, which involves sequentially attending to and processing individual sources of information, generally takes longer compared to global processing, which involves simultaneous processing of multiple sources (Navon, 1977). Therefore, it is plausible that players with mTBI, who may engage in locally processing visual information, require additional time to effectively analyze all the available cues for accurate anticipation of deceptive actions (i.e., wait to see if the player would change direction). This is consistent with our findings in Chapter 3, where individuals with a recent history of mTBI were observed to exhibit slower performance in the local condition (i.e., attending to the small letters) compared to the global condition (i.e., attending to the overall structures) of the Navon task. While it is possible that players with a history of mTBI in the present study were more accurate because they took longer to respond, this is deemed unlikely, because the temporal occlusion paradigm used in the study provided all the visual information before the occlusion point. This means that participants had access to all the necessary information to make their decision before the occlusion occurred. Therefore, if participants took longer to respond after the occlusion, it could be speculated that they spent more time thinking over their decision before responding (e.g., Sherwood, Smith, & Masters, 2019).

A number of limitations of the current study warrant discussion. First, the cross-sectional design of our study posed limitations in assessing individuals immediately after sustaining an mTBI. By including participants who had experienced an mTBI within the last 12 months, we were unable to establish causality between mTBI and anticipatory performance. Therefore, our findings may not accurately represent the acute or chronic stages of mTBI and cannot be generalized to all individuals with mTBI. To address this concern, a longitudinal study should be conducted to investigate the evolution of anticipatory performance following an mTBI. This approach would involve initial assessment of anticipatory performance immediately post-injury and repeated evaluations throughout the recovery period. Second, verbal responses were used to measure response accuracy and time. However, verbal responses alone do not provide an understanding of the perceptual skills that may underpin superior anticipatory performance in players with mTBI. Thus, future studies should consider incorporating eye tracking technology to examine whether players with a history of mTBI exhibit more efficient visual search strategies. Third, the use of a temporal occlusion paradigm in our study did not provide insight into the specific cues utilized by the participants. Therefore, to gain a deeper understanding of how players pick up information following a mTBI, future studies should consider employing a spatial occlusion paradigm, which masks or obscures specific areas or cues within the visual field. By selectively blocking certain visual information, researchers can examine which cues players with mTBI rely on when anticipating actions.

Our results suggest that expert rugby players with a history of mTBI were significantly more accurate than players without a history of mTBI when anticipating deceptive and non-deceptive changes of direction. However, players with a history of mTBI also took significantly longer to respond than players without a history of mTBI. Thus, the results from the present study should be interpreted with caution. The current investigation uncovers some novel findings that future research should seek to clarify while examining the underlying perceptual-cognitive mechanisms associated with mTBI.

Chapter 6

General Discussion

6.1 Aims and key findings

The aim of Chapter 2 was to determine whether people with a history of mTBI had a reduced tendency to perceptually group elements into a cohesive whole. The results of the first experiment showed size judgements by people with a history of mTBI were more accurate in the context condition (Ebbinghaus illusion) compared to controls. To further investigate whether these findings could be replicated, a different size-contrast illusion, the Müller-Lyer illusion was utilized in Experiment 1b of Chapter 2. Consistent with the findings from Experiment 1, size judgements by people with a history of mTBI were found to be significantly more accurate in the context condition compared to controls. Taken together, the findings from both experiments suggest that more accurate size judgements by people with a history of mTBI may derive from an impaired ability to perceptually group visual stimuli in near proximity (i.e., reduced global processing bias).

In Chapter 3, to confirm the assumption that people with a history of mTBI may have reduced global processing bias, we administered the Navon task, which is a validated tool to assess global and local processing. Our findings revealed that people with a recent history of mTBI (within 12 months) demonstrated a reduced global processing bias. Conversely, individuals who sustained their most recent mTBI more than one year earlier displayed the same global processing bias that control participants displayed. We concluded that global processing abilities may return to normal levels by one year after the injury, potentially as a result of restoration of functional and structural networks in the brain.

In Chapter 4, we examined whether people with a history of mTBI had a higher propensity to consciously monitor and control their movements. The results showed that people with a history of mTBI had a higher propensity for movement specific reinvestment than controls. In addition, we found that time since most recent mTBI was negatively associated with the conscious motor processing subscale of the MSRS. We argued that during the early stages of recovery, people with mTBI may have a greater tendency to consciously control their movements to avoid pain, re-injury, or trauma.

Chapter 5, investigated the effect of mTBI on anticipation of deceptive and non-deceptive movements. The results revealed that people with a history of mTBI were significantly more accurate than controls when anticipating both deceptive and non-deceptive movements. People with a history of mTBI were also shown to take significantly longer to respond than controls.

6.2 Implications and Considerations

6.2.1 Visual integration deficits following mTBI: implications of structural deficits in mTBI

This thesis presents the first substantial body of empirical work to suggest that people with a recent history of mTBI (within 12 months) process visual information in a deconstructive way (i.e., in fragments), resulting in a reduced tendency to integrate local information into global wholes. This pattern of visual processing has also been observed in other patient groups, including Autism Spectrum Disorders (Dakin & Frith, 2005) and Schizophrenia (Silverstein & Keane, 2009). The underlying mechanism for this deficit in visual integration remains unclear, but disruptions in long-range connections have been proposed as a potential cause (Angelucci et al., 2002).

Although the structural deficits were not investigated in this thesis, evidence suggests that diffuse axonal injury (DAI) is commonly present in most cases of TBI (Johnson et al., 2013). DAI involves the disruption of long-range axonal connections throughout the brain, leading to impaired communication between different brain regions and affecting the integration and coordination of neural activity (Smith, Hicks, & Povlishock, 2013; Ubukata et al., 2013). These long-range connections involve both feedforward and feedback projections, which are essential for integrating information across different hierarchical levels of the visual system (Barzegaran & Plomp, 2022). Feedforward projections originate from lower-level visual areas, such as primary visual cortex (V1), and transmit sensory information to higher-level visual areas (i.e., secondary visual cortex, V2), contributing to the initial processing of visual features (Briggs, 2020; Semedo et al., 2021). Feedback projections, on the other hand, originate from higher-level visual areas (V2) and transmit information to lower-level visual areas (V1), providing contextual information (i.e., prior knowledge) to guide the interpretation of incoming sensory information (Kafaligonul, Breitmeyer, & Ogmen, 2015). Together, feedforward and feedback projections facilitate the integration of visual information across different levels of the visual hierarchy, enabling the perception and recognition of visual objects. Therefore, disruption of long-range connections following DAI, may lead to impaired integration of visual information, as observed in Chapters 2 and 3.

Future studies should consider measuring structural and functional disruptions of long-range connections during visual integration tasks in people with a history of mTBI. One approach is to use diffusion tensor imaging (DTI) to examine structural connectivity between brain regions (Dailey et al., 2017). DTI measures the integrity and organization of white matter tracts, which are responsible for long-range connectivity. By analyzing fractional anisotropy (i.e., a measure of the directionality and coherence of water diffusion within white matter) and the total number of white matter fibers, the extent of damage to these connections can be assessed (Borich et al., 2013). Furthermore, functional magnetic resonance imaging (fMRI) studies have shown that in healthy individuals, visual integration tasks activate visual areas, such as V2, as well as visual areas involved in shape processing, such as extrastriate areas V3, V4, the lateral occipital cortex, and posterior fusiform regions (Altmann, Bulthoff, & Kourtzi, 2003; Altmann, Deubelius, & Kourtizi, 2004; Kourtzi et al., 2003; Silverstein et al., 2009). However, to the best of our knowledge, no study has used fMRI to investigate the integration of spatially distinct elements into coherent percepts in people with a history of mTBI. Thus, researchers should use fMRI to investigate abnormal visual integration in people with a history of mTBI, to clarify the contributions of activation changes in visual areas during visual integration tasks.

6.2.2 Visual integration deficits: implications for a narrow spotlight of attention in mTBI

Another aspect that deserves consideration as a possible influence on performance in visual integration tasks is spatial attention efficiency. Spatial attention plays a crucial role in integrating information by selectively focusing on specific locations within the visual field (Carrasco, 2018). However, in addition to orienting attention towards a specific location, it is also necessary for attentional focus to be adjustable in size (Ronconi et al., 2012). This ability, controlled by the right frontal eye fields, enables individuals to process visual stimuli either within a narrow (zoomed-in) or across a wide (zoomed-out) area of their visual field (Ronconi et al., 2012). A useful metaphor for understanding attentional distribution is camera's zoom lens – attention navigates through space and dynamically expands or contracts over its target, similar to adjusting the camera's field of view (Eriksen & St. James, 1986; Greenwood & Parasuraman, 1999).

Efficient spatial attention involves both zoom out and zoom in attentional mechanisms (i.e., the ability to distribute the attentional resources to a small or large portion of the visual field). However, researchers have found that in some clinical populations, such as Autism Spectrum Disorder and Schizophrenia, as a result of weakened top-down processing, individuals display a zoom-out attentional impairment, suggesting that attentional resources are rigidly allocated to a narrow region of the visual field (Elahipanah, Christensen, & Reingold, 2010; Ronconi et al., 2012). As a consequence, these individuals display inefficient integration of visual information because some of the visual information is outside, their attentional focus.

Psychological factors such as anxiety, have also been found to narrow spatial attention, which may in turn enhance local processing and/or compromise global processing (Wegbreit, Franconeri, & Beeman, 2015). The narrowing of spatial attention under anxiety can be explained by the Attentional Control Theory (Derakshan & Eysenck, 2009; Eysenck et al., 2007), which proposes that anxiety impairs the ability to disengage attention from threat-related information. As a result, individuals with anxiety tend to exhibit an attentional bias towards threat-related information, while simultaneously inhibiting the processing of non-threatening stimuli. This impaired attentional control may subsequently lead to a narrowing of spatial attention as hypervigilance towards threatening stimuli hijacks the attentional resources required for efficient spatial attention (Fawver & Janelle, 2019). Although zooming mechanisms have never been investigated in people with mTBI, it is important to note that mTBI is known to be a risk factor for anxiety (Lamontagne et al., 2021). Furthermore, previous research has shown that people with a history of mTBI exhibit enhanced attentional resource allocation to threat-related stimuli (Mäki-Marttunen et al., 2015). Therefore, it is plausible to speculate that following an mTBI individuals may develop symptoms of anxiety related to concerns, such as fear of another injury, enduring long-term cognitive impairments or the development of neurological condition later in life (e.g., dementia)(Lamontagne et al., 2021). Consequently, anxiety may cause people with a history of mTBI to focus attention on the most salient stimulus in their environment, which can result in a narrowed focus of attention and difficulty in expanding the scope of attention to include other stimuli within the visual scene (i.e., reduced global processing bias) (Najmi et al., 2011). However, future work is required to first examine whether elevated anxiety is associated with a local processing bias following mTBI. In addition, it is worth investigating whether people with a history mTBI display a narrowed focus of attention, and if it is a possible mechanism underlying impaired visual integration performance.

One common method to investigate attentional spotlighting is through the gaze-contingent paradigm. The gaze-contingent paradigm, developed by McConkie and Rayner (1975), involves masking the visual display outside a specific window that is linked to the gaze of the subject. By manipulating the size of the window and observing its effect on performance, researchers can determine the extent to which information from regions outside the window is processed during a single eye fixation. If reducing the window size impairs performance, it suggests that information from outside the window is normally processed. On the other hand, if performance is unaffected, it can be assumed that the information outside the window has little impact on the normal processing of visual information. As such, the gaze-contingent paradigm provides a method for measuring visual span (i.e., the region from which visual information is extracted during a single eye fixation). Thus, future work should consider employing a similar paradigm in people with a history of mTBI to investigate their visual attention spotlight.

6.2.3 Increased conscious motor processing following mTBI: implications of sensory integration deficits

The findings from Chapter 2 and 3 suggest that individuals with a history of mTBI have a reduced tendency to automatically process visual information globally, and instead focus on the local details of a visual stimulus. This reduced tendency may also extend to the processing of movements, where individuals with mTBI consciously attend to the details and mechanics of their movements.

Our findings in Chapter 4 support this assumption, as individuals with mTBI demonstrated a higher propensity for movement-specific reinvestment, indicating a tendency to consciously process their movements. We argued that people with a history of mTBI may consciously control their movements to avoid pain, re-injury, or trauma. However, it is important to note that, in addition to anxiety and fear, mTBI-related changes in sensory integration may also increase the tendency to consciously control movements. For example, to maintain balance, sensory information from visual, vestibular, and proprioceptive/somatosensory systems needs to be integrated in the brain (Gera et al., 2018; Martini et al., 2022). Research has found that people with a history of mTBI rely significantly more on visual cues during a postural control task than healthy controls, indicating a potential deficit in integrating sensory information from other sources (Dana-Dos-Santos, Driusso, & Degani, 2022; Gera et al., 2018). The exact mechanisms underlying this reduction in sensory integration in mTBI are not fully understood. However, it is believed that mTBI can disrupt the neural pathways involved in sensory integration, leading to impaired communication between sensory and motor regions of the brain (Martini et al., 2022). For example, people with a history of mTBI, have been observed to display reduced structural connectivity in frontal, parieto-premotor, visual, subcortical, and temporal areas due to DAI (Caeyenberghs et al., 2012). In addition, this disruption in structural connectivity is associated with poorer postural control following mTBI (Caeyenberghs et al., 2012). This suggests that DAI may interrupt the pathways meditating the sensory integration required for postural control. As a consequence, people with mTBI may need to allocate more attentional resources to maintain posture, which may increase the tendency to consciously control movements. This notion finds support from studies conducted in people with Parkinson’s disease. For example, people with Parkinson’s disease demonstrate abnormal electrical oscillatory frequencies when they walk, which is attributed to reduced dopaminergic neurons in the basal ganglia (Nwogo, Kammermeier, & Singh, 2022). This reduction in dopaminergic neurons impairs the processing of proprioceptive information (i.e., sensory cues regarding limb position in space) (Konczak et al., 2009). As a result, individuals with Parkinson’s disease are unable to efficiently use proprioception to guide their movements (Boonstra et al., 2008). Thus, to compensate for this problem, individuals with Parkinson’s disease attempt to consciously control the mechanics of their movements.

Currently, movement automaticity in people with a history of mTBI remains relatively unexplored, and research on cortical activity during motor tasks in this population is scarce. Thus, assessing cortical activity during a motor task may provide clarity into the implications of mTBI history on motor behaviors.

6.2.4 Implications of structural changes following mTBI: mechanisms of integration recovery

The findings from Chapters 3 and 4 suggest that integration deficits seem to recover or return to normal levels over time following mTBI. This is consistent with current literature that shows most individuals who have sustained an mTBI, demonstrate reduced cognitive and affective symptoms as time passes since injury (Karr, Areshenkoff, & Garcia-Barrera, 2014; McCrea et al., 2003). Although we did not measure structural brain changes in this thesis, previous neuroimaging studies have found that during the first 12 months of recovery from mTBI there is significant remodeling within regions of the cortex that are involved in visual attention, information processing, psychomotor speed, and emotional regulation, and that these structural changes relate to improved performance (Killgore et al., 2016).

6.2.5 Implications for visual search assessment following mTBI

In Chapter 5, it was evident that individuals with mTBI exhibited greater accuracy when anticipating both deceptive and non-deceptive movements. This accuracy may be attributed to the type of visual search strategy employed by expert athletes following an mTBI. Within the context of sports, expert athletes typically employ a visual search strategy characterized by fewer fixations of longer gaze duration (Mann et al., 2007). That is, experts tend to focus more on central regions of an opponent's body (such as the trunk) while using peripheral vision to monitor movements from the arms and legs, whereas novices tend to focus mostly on distal regions of the body (arms or legs) (Hausegger et al., 2019; Ripoll et al., 1995; Williams & Elliott, 1999). Thus, experts are able to detect early motion cues by observing the entire movement form around centrally located fixations, while briefly shifting attention and gaze to distal segments to clarify motion from important regions (Ripoll et al., 1995). Although visual search strategies have never been examined in athletes following an mTBI, research suggests that people with a history of mTBI may have a greater tendency to employ a serial visual search strategy (i.e., only one stimulus is attended at a time). For example, Rasmussen et al. (2008) observed that when people with a history of mTBI performed a dual task involving both a visual search task and a motor task, they displayed increased cortical activation in the regions associated with each of these tasks, as well as heightened activity in areas not activated during single-task performance, the bilateral medial superior frontal gyrus and left cingulate sulcus. These areas consist of extended visual search networks, which were not activated to the same extent by the control group (Kübler, Dixon, & Garavan, 2006), further suggesting that people with mTBI may undergo a shift from the efficient automatic parallel strategy typically employed during visual search to a more effortful serial method (Treisman, 1991). However, the adoption of a serial method of visual search has both advantages and disadvantages for anticipatory performance. One advantage is that a serial search allows for a more thorough and systematic examination of the visual field, which can enhance the detection of relevant cues and increase the accuracy of anticipation performance. Additionally, a serial search can facilitate object-based attention, where attention is prioritized to specific objects or stimuli, leading to more efficient processing and selection of relevant information (Nishida et al., 2014). On the other hand, a serial search can be time-consuming and may require more cognitive resources compared to a parallel search (Dosher et al., 2010). This can potentially lead to slower response times and reduced efficiency in overall anticipation performance, which may explain the slow response times found in the mTBI group in Chapter 5. Thus, the adoption of a serial method of visual search may improve anticipation accuracy through enhanced attentional prioritization and thorough examination of the visual field, but it may also come with potential drawbacks, such as increased time and cognitive demands.

Future work examining visual search strategies in athletes following an mTBI is therefore warranted. Researchers could explore the use of pupillometry, which might provide insights into visual search strategies or mechanisms because changes in pupil diameter are reliably associated with cognitive effort (Cabestrero, Crespo, & Quirós, 2009; Granholm & Steinhauer, 2004; van der Wel & van Steenbergen, 2018). Studies have shown that larger pupil dilation is associated with increased cognitive load (Jackson & Sirois, 2009; Koelewijn et al., 2015). In addition to pupillometry, researchers may also analyze other eye-tracking metrics, including fixation duration, saccade amplitude, and scan path patterns. These metrics can provide information about an athlete's visual exploration patterns, such as the duration of fixations on specific areas of interest, the distance and speed of eye movements between fixations, and the overall scan path followed during the task. By combining these metrics with pupillometry data, researchers may be able to obtain a comprehensive understanding of an athlete's visual search strategies following mTBI.

6.3 Practical applications

6.3.1 Visual illusions as a diagnostic tool

The findings of this thesis suggest that visual illusions can be a useful tool for probing visual integration deficits following mTBI. By utilizing a tablet-based application that presents visual illusions and tracks eye movements, researchers may be able to enhance the diagnosis of mTBI by measuring size discrimination accuracy. This approach would provide an objective marker for assessing both visual integration deficits and the visual search strategies employed by individuals with mTBI. In addition, this tool has potential to offer a fool-proof measure of mTBIs as players cannot easily manipulate their gaze responses or size estimates when judging illusions. Thus, incorporating visual illusions as a sideline assessment tool could be valuable in the diagnosis, treatment, and rehabilitation of individuals with mTBI. However, further research is needed to validate the effectiveness of this approach and explore its potential applications in clinical settings.

6.3.2 Prism adaptation training to reduce local processing bias

Prism adaptation has been shown to influence attentional orienting mechanisms (i.e., the ability to engage, disengage and shift focus), with participants showing changes in voluntary attention after adaptation to leftward or rightward shifting prisms (Bultitude et al., 2009; Nijober et al., 2008). Prism adaptation training involves wearing optical prisms and repeatedly making pointing movements to targets. The prisms induce a sensory mismatch, requiring individuals to adjust their motor movements to align with the shifted visual input. After the prisms are removed, individuals experience a negative after-effect, where pointing or throwing is shifted to the side opposite of the prismatic displacement (van der Kamp, Steenbergen, & Masters, 2017).

Prism adaptation has been found to reverse the local processing bias in patients with right temporo-parietal junction lesions (Bultitude et al., 2009). Lesions to this area are associated with hyperattention to local details and difficulty perceiving global structures, which contributes to neglect. Prism adaptation has been found to shift visual field representation from the right to left inferior parietal lobule, redirecting visual input to the dorsal attentional system and restoring balance between its left- and right-hemispheric components. Additionally, prism adaptation can influence non-lateralized spatial attention in healthy individuals, as demonstrated by a significant reduction in global processing bias after adaptation to leftward-shifting prisms (Reed & Dassonville, 2014). Taken together, these findings suggest that rightward prism adaptation may alleviate local processing bias by improving attentional orienting mechanisms. Therefore, it is possible that prism adaptation paradigms could be used to reduce the local processing bias in people with a history of mTBI, improving their ability to perceive global structures and integrate information.

6.4 Limitations

The primary limitation of the research conducted in this thesis was the reliance on self-reported history of mTBI. This reliance presents several noteworthy issues. First, self-reporting is susceptible to recall bias, as individuals may not accurately remember or disclose past mTBI incidents. This limitation can lead to an underestimation or overestimation of the actual prevalence of mTBI within the study population, thereby compromising the reliability of the findings. Second, self-reporting may also be influenced by social desirability bias, as participants might provide responses that they believe align with societal expectations or avoid disclosing certain information due to stigma or personal reasons. Additionally, relying solely on self-report without objective confirmation, such as medical records or diagnostic assessments, may introduce uncertainty about the validity of reported mTBI events. This can make it challenging to distinguish between actual mTBI cases and other conditions or events that may have caused similar symptoms.

To mitigate these limitations, researchers could employ a combination of self-report data and objective measures when studying mTBI. For example, they may use medical records, neuroimaging, and neuropsychological assessments to validate and complement self-reported information. This approach would help enhance the reliability and validity of research findings related to mTBI.

Methodological limitations were also evident in experimental Chapter 2, 3, and 4. Due to Covid-19, all of these experiments had to be conducted online. As a result, it was not possible for us to assess participants' immediately after sustaining an mTBI. These limitations can be easily addressed by incorporating these experiments into sideline or onsite medical assessments.

6.5 Conclusion

This thesis presents evidence indicating an increased tendency to deconstruct visual and movement information following mTBI. These novel findings raise several questions for future research, which have been addressed within this thesis. Furthermore, these findings have important implications for rehabilitation specialists, who could consider integrating prism adaptation training paradigms to reduce local processing of visual information. Additionally, the utilization of visual illusions holds promise as a valuable tool for assessing visual integration deficits following mTBI.

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Appendix 1: Co-authorship forms

Co-Authorship Form

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Thesis chapter:

Reduced influence of perceptual context in mild traumatic brain injury is not an illusion

Nature of contribution by PhD candidate	Main investigator, conception, design, data collection, analysis, interpretation, drafting, revisions
Extent of contribution by PhD candidate (%)	75%

CO-AUTHORS

Name	Nature of Contribution
Liis Uiga	Interpreting, comments
Brett Langley	Comments
Rich Masters	Significant at all stages; primary supervisor

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Prof Rich Masters	R.S.W. Masters	27 Sept. 2023
Dr Liis Uiga	L. Uiga	28 Sept 2023
Dr Brett Langley	[illegible]	28/09/2023

July 2015

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Thesis chapter:

Reduced global processing bias and mild traumatic brain injury

Nature of contribution by PhD candidate	Main investigator, conception, design, data collection, analysis, interpretation, drafting, revisions
Extent of contribution by PhD candidate (%)	75%

CO-AUTHORS

Name	Nature of Contribution
Liis Uiga	Comments
Brett Langley	Comments
Rich Masters	Significant at all stages; primary supervisor

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Thesis chapter:

Movement specific reinvestment and mild traumatic brain injury

Nature of contribution by PhD candidate	Main investigator, conception, design, data collection, analysis, interpretation, drafting, revisions
Extent of contribution by PhD candidate (%)	75%

CO-AUTHORS

Name	Nature of Contribution
Liis Uiga	Interpreting, comments
Brett Langley	Comments
Rich Masters	Significant at all stages; primary supervisor
Nick Draper	Comments

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Thesis chapter:

Anticipation of deceptive and non-deceptive movements in club rugby players with a history of mild traumatic brain injury

Nature of contribution by PhD candidate	Main investigator, conception, design, data collection, analysis, interpretation, drafting, revisions
Extent of contribution by PhD candidate (%)	75%

CO-AUTHORS

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Liis Uiga	Interpretation, Comments
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