Visual Illusion Susceptibility Following Mild Traumatic Brain Injury in Adolescents

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Abstract

Following Mild Traumatic Brain Injury (mTBI), clinical symptoms often resolve before full physiological recovery is complete, highlighting the need for objective indicators of ongoing neural disruption. Visual illusions, which rely on contextual visual processing, may provide a sensitive behavioural marker of subtle perceptual changes following concussion. While reduced susceptibility to visual illusions has been demonstrated in adults following mTBI, little is known about whether similar effects are observed in adolescents. The present study examined susceptibility to visual illusions in adolescents with a history of mTBI and in a TBI-free comparison group. A secondary aim was to explore associations between illusion performance, age, and post-concussive symptom burden within the mTBI group. Adolescents with a history of mTBI and age-matched TBI-free comparison participants completed two visual illusion tasks (Ebbinghaus and Müller–Lyer), each comprising context (illusion) and no-context trials. Post-concussion symptoms were assessed using developmentally appropriate versions of the Post-Concussion Symptom Inventory (PCSI). No significant group differences were observed on context trials of either illusion task. Adolescents with mTBI showed significantly lower accuracy on no-context trials of the Ebbinghaus task than comparison participants. Age was not significantly associated with illusion susceptibility in either group. Within the mTBI group**,** post-concussion symptom severity was not significantly related to performance on Müller–Lyer or Ebbinghaus context trials for either parent-reported or adolescent self-reported symptoms. These findings suggest that visual integration accuracy appears comparable to typical performance in adolescents assessed at a relatively long interval following mTBI, which may reflect recovery or resolution of any earlier disruption. However, whether visual integration was affected during the acute or subacute stages of injury remains unclear.

Future research is needed to determine whether visual-illusion paradigms provide a useful, objective complement to symptom-based assessment for detecting subtle perceptual differences following paediatric mTBI.

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Introduction

Traumatic brain injury (TBI) is a significant global health concern and a leading cause of death and disability, particularly among children and young adults (Nwafor et al., 2022). TBI refers to an injury to the brain resulting from an external mechanical force, such as a blow, bump, jolt, or penetrating injury to the head, which disrupts normal brain function (Jha & Ghewade, 2022). Mild traumatic brain injury (mTBI), commonly referred to as concussion, represents the most frequent form of TBI, accounting for up to 90% of all cases (Maas et al., 2022; Silverberg et al., 2020). mTBI is typically defined by no loss of consciousness or a brief loss of consciousness (< 30 minutes) and a short period of post-traumatic amnesia (< 24 hours) (Ginsburg & Smith, 2025).

Given that the majority of TBIs are classified as mild, global and paediatric TBI incidence estimates largely reflect the burden of mTBI. Recent Global Burden of Disease estimates suggest that approximately 50 - 60 million new TBI cases occur each year worldwide, with children and adolescents representing one of the groups at highest risk for hospitalisation and longer-term disability (James et al., 2019; Maas et al., 2022). This injury disproportionately impacts children, adolescents, and young adults, with a substantial proportion of cases resulting from sports-related injuries, falls, and motor vehicle accidents (Konigs et al., 2015). Despite increased public and clinical awareness, concussion research has predominantly focused on sports-related injuries in adolescents and adults, resulting in limited understanding of concussion epidemiology, mechanisms, and acute presentation in younger paediatric populations (Davis et al., 2017; Santana et al., 2026).

Children and adolescents are at an increased risk of developing an mTBI due to high rates of participation in contact sports, play activities, and risk-taking behaviours (Haste et al., 2025;

Nwafor et al., 2022; Russell et al., 2017). Under-reporting is common among young populations, partly because children may struggle to recognise or accurately articulate their symptoms (Russell et al., 2017; Zemek et al., 2016). In younger children, clinicians must also rely heavily on parents or caregivers to report injury mechanisms and symptom changes, which can further complicate accurate diagnosis and monitoring (Santana et al., 2026).

Although mTBI is often regarded as an acute event, growing evidence indicates that this injury can be associated with longer-term changes in brain function and an increased risk of persistent outcomes, including chronic symptoms that disrupt physical, cognitive, emotional, and behavioural functioning, as well as disability and neurodegenerative disease (Maas et al., 2022; McMahon et al., 2014; Silverberg et al., 2020). In children and adolescents, mTBI is especially challenging because diverse injury mechanisms, pre-injury differences, and developmental factors create highly variable patterns of impairment and recovery (Bodien et al., 2023).

The pathophysiology of mTBI involves complex mechanisms, including diffuse axonal injury (DAI), which occurs when mechanical forces stretch or tear brain fibres during rapid acceleration and deceleration of the head (Konigs et al., 2015). These biomechanical forces trigger a neurometabolic cascade, characterised by ionic imbalance, inflammation, and disrupted neural connectivity (Alnawmasi et al., 2022; Konigs et al., 2015). These physiological changes frequently occur in the absence of visible structural abnormalities on conventional neuroimaging techniques such as computed tomography (CT) or magnetic resonance imaging (MRI), limiting their clinical utility for diagnosis and monitoring of recovery (Haste et al., 2025; Konigs et al., 2015; Russell et al., 2017). This contributes to marked heterogeneity in symptom severity and functional outcomes, even among children with the same injury classification (Bodien et al., 2023).

Symptom Profile and Recovery in Children

Symptoms following mTBI in children are complex and varied, typically affecting physical, cognitive, emotional, and sleep-related domains (Haas et al., 2019). Physical complaints such as headaches, dizziness, balance problems, light and noise sensitivity, and nausea are commonly reported in the acute phase (Alnawmasi et al., 2022; Konigs et al., 2015). Cognitive issues often include slowed information processing, attention difficulties, and poor memory or concentration (Russell et al., 2017; Tuersunjiang et al., 2025). Emotional changes, such as irritability, nervousness, and mood swings, may also emerge and, in some cases, intensify later in the recovery period (Russell et al., 2017). Sleep disturbances, including delayed sleep onset, fragmented sleep, and daytime fatigue, are frequent and can significantly affect recovery outcomes (Barlow et al., 2021). Studies indicate that although most children recover spontaneously within weeks, a significant subgroup experiences persistent impairments in cognition, mood, and sensory integration (Leddy et al., 2021; Marzolla et al., 2025; Mavroudis et al., 2024). These subtle outcomes are frequently missed by broad global outcome measures, as they tend to lack sensitivity to detect small yet clinically significant changes (Bodien et al., 2023).

Although many children recover within two to four weeks, a significant proportion experience persistent post-concussion symptoms (PPCS), defined as symptoms lasting longer than one month (Chadwick et al., 2022; Gudymenko et al., 2025; Silverberg et al., 2020). Estimates suggest that 11–30% of children and adolescents develop PPCS, with at least 2% continuing to experience symptoms one year post-injury (Heyer et al., 2016; Thorstensen et al., 2026). Factors associated with prolonged recovery include higher initial symptom burden, sleep disturbance, pre-existing mental health conditions, and older age within the range (Barlow et al., 2021; Heyer et al., 2016). Recovery trajectories also differ by symptom type:

physical symptoms often resolve earlier, whereas cognitive and emotional symptoms may linger and interfere with return to school and daily life (Zemek et al., 2016).

Return to school (RTS) following mTBI is a critical component of paediatric recovery. Unlike return-to-play protocols in sports, the return-to-learn process requires tailored academic accommodations to reduce symptom exacerbation and cognitive overload. Philipson et al. (2021) emphasise a student-centred return-to-learn care plan that includes temporary adjustments such as reduced workload, scheduled breaks, and modifications to screen use or lighting. A gradual reintroduction to cognitive tasks, while closely monitoring symptoms, is recommended to prevent setbacks and promote recovery. Clinical guidelines now stress the importance of coordination between healthcare providers, schools, and families to optimise school reintegration (Teel et al., 2019).

In New Zealand, this approach is reflected in a graduated return-to-school framework, whereby most children resume usual activities within three to four days following a mTBI. After medical clearance, a period of relative rest is recommended for the first 24–48 hours to allow initial recovery, with reduced exposure to screens and cognitively demanding tasks. This is followed by a graduated return-to-school approach, beginning with light daily activities at home (such as short periods of reading or gentle movement), progressing to brief school-related tasks completed at home, and then a partial return to school. During this phase, temporary adjustments may include shortened school days, reduced academic demands, and access to quiet rest spaces. Full-time school attendance is gradually resumed once the child can tolerate a full school day without more than mild symptom exacerbation. This staged approach supports recovery while minimising symptom burden and promoting a safe reintegration into learning environments (Kids Health, 2024; Starship, 2024). While return to school is prioritised following concussion, return to sport typically occurs at a later stage once cognitive demands are tolerated and symptoms have stabilised. Nevertheless, evidence

from a systematic review indicates that in approximately 80% of published studies, children returned to sport within 21 days post-injury, suggesting that progression back to physical activity often occurs relatively quickly (Wait et al., 2023).

Despite the clinical importance of symptom tracking, the assessment of mTBI recovery largely relies on subjective symptom reporting. The Post-Concussion Symptom Inventory (PCSI) is a widely used paediatric measure with developmentally tailored versions for children aged 5-18, including both self-report and parent-proxy report formats (Gioia et al., 2009). While symptom inventories provide valuable insight into subjective recovery, symptom resolution does not necessarily reflect full physiological or functional recovery of the brain (Bodien et al., 2023; Silverberg et al., 2020). Subjective reports may also be influenced by contextual factors, such as pressure to return to school or sport, leading to under-reporting of ongoing difficulties (Meier et al., 2015). Emerging evidence further suggests that physiological recovery may lag behind symptom improvement, increasing the risk of premature return to cognitively or physically demanding activities (Kamins et al., 2017).

To address the limitations of symptom-based assessment, researchers have explored more objective approaches to assess concussion recovery, including neurocognitive testing, vestibular and oculomotor screening, and, more recently, neuromodulation and neuroimaging techniques. Functional imaging and electrophysiological methods such as electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) show promise in detecting subtle brain changes following mTBI (Buhagiar et al., 2020). However, these tools are not yet widely implemented in routine paediatric care due to high cost, limited accessibility, and the need for specialised technical expertise. As a result, there remains a critical need for sensitive, developmentally appropriate, and clinically feasible objective markers of recovery following paediatric mTBI (Tomaiuolo et al., 2023).

Emerging methods such as the Single Item Recovery Question (SIRQ) have also been validated as a simple yet effective measure of recovery status in children. Hansen et al. (2023) found the SIRQ to be sensitive to symptom improvement over time and aligned well with clinical judgments of recovery, providing an efficient add-on to longer symptom checklists. Nevertheless, symptom recovery does not necessarily indicate full restoration of underlying cognitive or perceptual processes (McInnes et al., 2017).

Given the reliance of everyday activities such as reading, classroom learning, and navigation on intact visual processing, examining visual perception provides a promising avenue for identifying subtle functional changes that may persist beyond symptom resolution. Children may report reduced symptom burden while experiencing ongoing, unrecognised difficulties in visual integration and sensory processing, particularly in systems that are still developing and vulnerable to injury. This dissociation highlights the importance of complementing symptom measures with objective assessments of perceptual function in paediatric mTBI.

Visual perception

Visual perception is a complex cognitive process through which the brain organises incoming visual stimuli to create a coherent and meaningful representation of the world. This involves recognising shapes, detecting motion, judging spatial relationships, and integrating multiple visual elements into a unified whole (Coren & Girgus, 2020). Two major neural pathways support these processes: the dorsal stream, which underlies motion detection, spatial localisation, and visuomotor coordination; and the ventral stream, which is responsible for object recognition, form perception, and detailed feature analysis (Alnawmasi et al., 2022). These pathways work together to support both basic sensory input and high-level cognitive interpretation of visual scenes.

Visual perception is not fully mature at birth. Basic visual acuity and contrast sensitivity develop quickly in infancy, whereas global form and motion perception, which rely heavily on dorsal stream maturation, develop more slowly, continuing into mid-to-late adolescence (Braddick & Atkinson, 2011). As children grow, they become more efficient at integrating local visual details into global patterns, which is vital for coherent shape recognition, reading, and tracking movement across a scene.

Visual symptoms are particularly prevalent after an mTBI, occurring in up to 90% of cases (Alnawmasi et al., 2022). These include blurred vision, light sensitivity, double vision, difficulty tracking moving objects, reading difficulties, and discomfort with visual motion or patterns (Armstrong, 2018). Such visual disturbances can persist for extended periods, significantly impacting daily activities such as reading, driving, and academic performance, especially in young individuals whose brains are still developing (Konigs et al., 2015). mTBI can impair global form and motion perception, functions which are critical for navigating dynamic, complex environments (Alnawmasi et al., 2022). In addition to visual disturbances, mTBI often disrupts multisensory integration, leading to dizziness, balance problems, and difficulties with auditory processing (Chan et al., 2025). These interconnected sensory issues highlight the way mild injuries can affect multiple functional systems simultaneously. Heightened sensitivity to light and sound, for example, can exacerbate other symptoms and prolong recovery (Chan et al., 2025).

Given the high prevalence of visual and sensory symptoms in paediatric mTBI, understanding how brain injury may disrupt the development and function of visual pathways is crucial, particularly the dorsal stream, which matures slowly and is vulnerable to damage (Alnawmasi et al., 2022; Braddick & Atkinson, 2011). Subtle deficits in visual integration can affect core activities such as reading, coordination, and classroom learning, yet may

remain undetected during routine clinical assessment of mTBI, which typically does not include detailed evaluation of higher-order visual processing.

Therefore, examining visual perception provides an important lens for identifying impairments that may not be captured by traditional symptom checklists. This approach is particularly suited to assessing recovery in young people whose brains are still developing, and visual illusions offer a practical method for examining these perceptual processes in detail.

Visual Illusions

Visual illusions demonstrate that human visual perception is complex and interpretative. Broadly defined, visual illusions occur when there is a mismatch between the physical properties of a stimulus and the way the stimulus is perceived (Todorović, 2020). These discrepancies highlight the brain's active role in constructing perceptual experience rather than merely recording sensory input.

Historically, illusions were often considered perceptual errors, which are failures of the sensory system to accurately represent the world. However, contemporary perspectives reject the notion that illusions represent malfunctions. Instead, illusions are now understood as byproducts of the brain's reliance on prior experience, context, and perceptual heuristics to efficiently interpret ambiguous or complex stimuli (Coren & Girgus, 2020; Zavagno, 2023). In this sense, illusions are not breakdowns in perception but rather demonstrations of how perception typically operates.

Different types of visual illusions arise from distinct mechanisms. Some stem from low-level sensory processes, such as brightness contrast or edge detection, while others emerge from high-level cognitive inferences about depth, size, or shape (Ditzinger, 2021). For example, geometric illusions such as the Müller-Lyer illusion exploit the brain's

interpretation of depth cues, with inward- or outward-facing arrowheads causing identical line lengths to appear different. In contrast, contextual illusions, such as the Ebbinghaus illusion, rely on surrounding context, where the perceived size of a central circle is influenced by the size of surrounding circles when judging size and spatial relationships (Coren & Girgus, 2020; Gentaz & Hatwell, 2004). Two of the most extensively studied visual illusions, the Müller-Lyer and Ebbinghaus illusions, demonstrate how contextual cues influence the perception of size and spatial relationships. These illusions are especially relevant in experimental research examining visual integration, as they rely on the brain's ability to interpret surrounding stimuli accurately.

Visual illusions demonstrate that perception is not a direct reflection of physical reality but rather a constructive process shaped by both the structure of the visual system and the brain's interpretation of sensory input. Research by Ditzinger (2021) suggests that the visual system favours simplicity and meaning, often prioritising efficient interpretation over precise physical accuracy. As a result, visual illusions are valuable tools for understanding how the visual system creates meaning from incomplete information.

Developmental studies have shown that children's susceptibility to certain illusions varies by age. For instance, younger children (under 10) tend to be more influenced by local visual features and are thus more susceptible to geometric illusions such as the Müller-Lyer illusion, which relies on depth and angle perception (Ditzinger, 2021; Gentaz & Hatwell, 2004). In contrast, older children and adolescents (ages 10–18) show increased susceptibility to contextual illusions such as the Ebbinghaus illusion, reflecting a maturing capacity for global contextual integration (Duemmler et al., 2008; Wincza et al., 2024). These age-related differences are thought to reflect ongoing development of top-down processing, attentional control, and functional connectivity within visual cortical networks.

The Müller-Lyer Illusion

The Müller-Lyer illusion is a well-known geometric optical illusion in which two horizontal lines of equal length appear unequal due to the shapes of their endpoints. Typically, the line with inward-pointing arrowheads (acute angles) appears shorter than the line with outward-pointing arrowheads (obtuse angles; Ditzinger, 2021; Todorović, 2020). This illusion arises from the brain's interpretation of the arrow shapes as depth cues, creating a false perception of three-dimensional space. Specifically, the inward-facing arrows are interpreted as indicating a near corner, while the outward-facing arrows suggest distant corners, leading the brain to misjudge the actual length of the lines (Howe & Purves, 2005; Todorović, 2020).

Susceptibility to the Müller-Lyer illusion varies across development, with younger children showing greater reliance on local visual features such as angles and line orientation when interpreting spatial information (Ditzinger, 2021; Gentaz & Hatwell, 2004). Notably, altered susceptibility to this illusion has also been observed following neurological disruption. Sidhu (2024) reported reduced susceptibility to the Müller-Lyer illusion in adults with mTBI, suggesting impairments in the use of depth and contextual cues. This aligns with evidence that mTBI commonly affects dorsal stream pathways involved in spatial integration and contextual processing (Alnawmasi et al., 2022). Together, these findings indicate that performance on the Müller-Lyer illusion reflects both developmental stage and the integrity of visual integration mechanisms.

The Ebbinghaus Illusion

The Ebbinghaus illusion, also known as the Titchener circles, illustrates how the perceived size of an object is affected by its surrounding context (Kirsch & Kunde, 2021). In

this illusion, two central circles of identical size appear different depending on the size and spacing of the surrounding circles. A central circle appears smaller when surrounded by larger circles and larger when surrounded by smaller ones (Ditzinger, 2021). This occurs because the brain relies on relative comparisons, using nearby objects as a reference point to assess size (Todorović, 2020).

Roberts, Harris, and Yates (2005) found that the magnitude of the Ebbinghaus illusion is influenced by both the size and distance of the surrounding inducers, suggesting that spatial proximity and contrast amplify contextual effects. This illusion highlights that perception is not absolute but is shaped by surrounding stimuli and has been widely used to examine how individuals integrate visual context. Developmental research by Duemmler et al. (2008) found that susceptibility to the Ebbinghaus illusion increases with age, reflecting a growing capacity for global contextual integration. This pattern is further supported by a recent systematic review by Wincza et al. (2024), which reported that across studies, children generally show increasing susceptibility to the Ebbinghaus illusion as they get older, although substantial variability exists depending on task design and measurement methods.

In contrast, evidence from adult populations suggests that disruptions to neural processing may alter this developmental pattern. Sidhu (2024) found that adults with a history of mTBI exhibited reduced susceptibility to the Ebbinghaus illusion, indicating diminished integration of surrounding visual context and a greater reliance on local visual information during size judgments.

Together, these findings suggest that while sensitivity to visual context typically strengthens across childhood, this process may be disrupted following mTBI. However, little is known about how mTBI affects visual integration during childhood and adolescence, when these perceptual systems are still developing.

Summary of the Literature and Direction of the Current Study

Assessing recovery following mTBI presents a significant challenge in clinical practice, particularly in paediatric populations. Traditional clinical tools often rely on subjective symptom reports, which may not fully capture the complexity of the injury, especially in younger populations where self-reporting may be unreliable or incomplete (Konigs et al., 2015). Advanced neuroimaging techniques, while valuable, are often unavailable or costly, limiting their practical application in routine clinical care. Additionally, these tools may lack the sensitivity required to detect subtle effects of mTBI (Shvedoff, 2025). This underscores the need for practical, objective measures that can effectively identify and quantify visual processing deficits in individuals with mTBI.

Recent research has highlighted the potential of visual perception tasks, particularly those involving susceptibility to visual illusions, as effective and accessible methods for identifying subtle impairments following mTBI. These tasks are not only practical for clinical use but also provide a non-invasive, child-friendly approach to assessing visual integration and contextual processing.

For instance, Sidhu (2024) conducted an experiment investigating whether individuals with a history of mTBI within the last 12 months show differences in global visual processing compared to individuals without mTBI. In this study, adult participants completed computer-based versions of the Müller-Lyer and Ebbinghaus illusions, which assess the brain's reliance on contextual cues to interpret size and depth information. Sidhu (2024) found that participants with a history of mTBI demonstrated significantly reduced susceptibility to both illusions compared to matched controls, suggesting an impaired automatic tendency to integrate local visual elements into a global percept.

Together, this body of work suggests that mTBI may alter the brain's typical bias toward global visual processing, which may not be fully captured by symptom-based assessments alone. Findings in adults indicate that visual illusions can reveal subtle disruptions in perceptual grouping that may not be captured by symptom checklists or standard neuropsychological measures. Accordingly, the present study investigates differences in illusion susceptibility between adolescents with a history of mTBI and adolescents without mTBI, examines age-related variation in susceptibility, and explores whether concussion symptom burden is associated with performance on these perceptual tasks.

Current Study

Previous research has demonstrated that mTBI can alter visual processing, particularly in tasks requiring global integration and perceptual grouping (Sidhu, 2024). However, this body of work has focused primarily on adult populations, and there remains limited empirical research examining illusion susceptibility following mTBI in children and adolescents, despite ongoing neurodevelopment during this period.

In parallel, post-concussion symptom burden is commonly used as an indicator of recovery in paediatric mTBI (Gioia et al., 2009; McCrory et al., 2013). Although symptom reports provide important clinical information, their relationship with objective measures of perceptual functioning remains unclear. To date, few studies have examined whether symptom burden is associated with performance on perceptual integration tasks following mTBI, and no studies have investigated this relationship using visual-illusion paradigms in paediatric samples.

Therefore, the current study seeks to address these gaps by examining susceptibility to visual illusions in children and adolescents with and without a history of mTBI. Specifically,

this study investigates whether illusion susceptibility differs between adolescents with and without a history of mTBI, and whether performance varies as a function of age and post-concussion symptom burden. Data were drawn from a New Zealand sample of children and adolescents recruited as part of a broader concussion research study. By extending illusion-based methods to a developmental population, this study aims to determine whether visual illusions can serve as a sensitive marker of subtle perceptual disruption following paediatric mTBI and to inform the development of more objective assessment tools for concussion recovery.

Based on previous research and the aims of the current study, the following hypotheses were tested:

(1) Adolescents with a history of mTBI will show reduced susceptibility to contextual (illusion) trials compared to TBI-free adolescents, while no group differences are expected on no-context trials for the Ebbinghaus and Müller-Lyer illusion tasks.
(2) Age will be differentially associated with susceptibility to the two visual illusions, such that susceptibility to the Ebbinghaus illusion will increase with age, whereas susceptibility to the Müller–Lyer illusion will decrease with age across adolescence.
(3) Post-concussion symptom burden will be associated with performance on visual illusion tasks within adolescents with a history of mTBI.

Method

Ethics

Ethical approval for this research was granted by the University of Waikato Human Research Ethics Committee (Health) [HREC(Health) 2025 #48], as part of the broader visual perception and mTBI study described above. All procedures complied with the University's Ethical Conduct in Human Research and Related Activities Regulations and the New Zealand Psychological Society Code of Ethics. This study was supported by a University of Waikato Strategic Research Fund Grant.

Participants

This study included two groups of children: an mTBI group and an age-and gender-matched TBI-free comparison group. All participants needed access to a computer with a keyboard to complete the visual-perception tasks.

Mild Traumatic Brain Injury Group

Participants from the mTBI cohort were recruited from the Concussion Recovery Assessment of New Zealanders in Adolescence and Childhood (CRANIAC) study. CRANIAC is a large, longitudinal research project based at the University of Waikato. An mTBI was defined as a direct or indirect force to the head that resulted in a brief disturbance of neurological function without structural abnormalities on standard neuroimaging, consistent with the Zurich Consensus Statement on Concussion in Sport and New Zealand concussion guidelines (Accident Compensation Corporation, 2026; Brain Injury Association of New Zealand, n.d.; McCrory et al., 2013). Diagnosis required the presence of one or more of the following symptoms: (a) somatic symptoms (e.g., headache, nausea, or vomiting); (b)

cognitive symptoms (e.g., confusion, slowed thinking, or feeling "in a fog"); (c) emotional symptoms (e.g., irritability); (d) physical symptoms such as loss of consciousness; (e) behavioural changes, and/or sleep disturbances, following the injury.

To be eligible for the CRANIAC mTBI group, participants were required to be between 5 and 17 years of age (inclusive) and to have received a recent diagnosis of concussion by a medical professional. Participants were typically identified through presentations at Waikato, Middlemore, North Shore, Waitakere, or Whangārei Hospitals; Urgent Care Centres across South Auckland and the Waikato/Bay of Plenty; or through general practice clinics in Auckland and the Waikato. However, adolescents from anywhere in New Zealand were eligible to participate, including those who self-referred, provided they had received an mTBI diagnosis.

Participants were excluded if they had: (a) a Glasgow Coma Scale score below 13 at any point post-injury (b) required neurosurgical intervention or general anaesthesia (c) had an intellectual disability that prevented valid completion of the assessments (d) had injuries resulting from non-accidental trauma from family violence (e) insufficient English proficiency to complete the tasks (f) multiple/severe trauma (only severe cases were excluded) (g) symptoms were not clearly attributable to trauma (e.g., post-seizure) (h) drug or alcohol intoxication at the time of injury and (i) previous participation in the study.

At the conclusion of the CRANIAC study, participating families were asked whether they were willing to be contacted about future research opportunities. Families who consented to this and had adolescents aged 10-19 years were approached to participate in the present visual perception study. Of those approached (n = 145), some declined participation (n = 15); others reported that they were unable to participate at the time but expressed interest in future involvement. Several did not reply or were unable to be contacted (n = 25). Forty-

four mTBI adolescents consented to participate in the visual-perception study, and 40 completed the full visual-perception assessment.

Age-and-Gender Matched TBI-Free Comparison Group

A group of adolescents were recruited as the comparison group for this study. Participants were recruited through community and university advertisements, as well as a recruit-a-friend or sibling approach to match the age and gender of the mTBI group. Adolescents who reported no lifetime history of concussion, defined as neither any clinician-diagnosed concussion nor any head injury that produced concussion-like symptoms (e.g., confusion, dizziness, headache, nausea, sensitivity to light or noise) were eligible to take part.

Comparison participants were screened using a parent-report eligibility questionnaire. The following question was used to confirm the absence of any concussion history: "Has your child ever been told by a doctor they have a concussion or brain injury or mTBI?" No other exclusion criteria were applied.

The final sample comprised 79 adolescents, including 40 participants with a history of mTBI and 39 comparison participants with no reported history of concussion. The demographic characteristics of the participants are summarised in Table 1. As shown in the table, the two groups did not differ significantly in age, sex distribution, or ethnicity. The TBI group had a mean age at injury of 12.41 years (SD = 2.39), and the mean time since the most recent injury was 27.84 months (SD = 7.89).

Table 1.

Demographic Characteristics of Participants

	Group				
	TBI		Comparison		
Adolescent Characteristics	(*n* = 40)		(*n* = 39)		Test of Difference
Male, *n* (%)	21	(52.50)	16	(41)	$\chi^2(1) = 1.04$, $p = .31$
Age (in years), *M (SD)*	14.55	(2.53)	13.44	(2.95)	$t(77) = 1.81$, $p = .08$
Classified Ethnicity					$\chi^2(3) = 4.37$, $p = .22$
Māori, *n* (%)	6	(15)	3	(7.70)	
Pacifica, *n* (%)	3	(7.50)	0	0	
NZ European, *n* (%)	23	(57.50)	27	(69.20)	
Other, *n* (%)	8	(20)	9	(23.10)	
Age at Injury (years), *M (SD)*	12.41	(2.39)	NA	NA	
Time since injury (in months), *M (SD)*	27.84	(7.89)	NA	NA	

Note. Values are reported as *n* (%) unless otherwise indicated. *M* = mean; *SD* = standard deviation; TBI = traumatic brain injury. Group differences were tested using chi-square tests for categorical variables and independent-samples *t* tests for continuous variables.

Design

This thesis forms part of a larger research program led by Professor Nicola Starkey, which examines visual perception following mild traumatic brain injury (mTBI) in adolescents [HREC(Health)2025#48]. The project extends findings from an earlier HRC-funded study on concussion recovery in children and adolescents (HDEC_19CEN183) by investigating whether susceptibility to visual illusions can serve as an objective indicator of ongoing physiological recovery after mTBI. Within this broader study, the current master's research focuses on

adolescent participants and explores group differences in visual-perceptual accuracy between those with and without a history of concussion.

This study used a cross-sectional case–control design to compare adolescents with a history of mTBI to individuals with no lifetime history of concussion. Assessments were conducted either in person at the University of Waikato (Hamilton or Tauranga) or remotely via Microsoft Teams, according to participants' preferences and logistical constraints. Questionnaires were administered in Qualtrics, and visual tasks were implemented in PsychoPy and deployed on Pavlovia.

The order of the visual perception tasks was counterbalanced across participants. The optional visual search task 'where's kiwi' was always completed at the end of the session.

Measures

The assessment session consisted of demographic questions, the PCSI, two visual-illusion tasks, and an optional visual-search task. Full descriptions of each measure/task are provided below.

Demographic Information

Demographic and background information were collected through Qualtrics-hosted questionnaires. Parents and/or caregivers reported their relationship to the participant**,** as well as their own gender, ethnicity, highest qualification, employment status, and household income**.** They also provided information about the participant's gender, ethnicity, and any diagnosed medical or developmental conditions (e.g., migraine, ADHD, learning disability, dyslexia, seizures, mental health, or sleep problems). For the mTBI cohort**,** participants indicated whether any additional mTBI had occurred since their participation in the CRANIAC study.

Post-Concussion Symptom Inventory (PCSI)

The Post-Concussion Symptom Inventory–2 (PCSI-2; Gioia et al., 2019) is a validated measure designed to assess concussion-related symptoms in children and adolescents across four domains: physical, cognitive, emotional, and sleep/fatigue. The measure includes developmentally tailored versions: two Child Forms (ages 5-6 and 7-12)**,** the Adolescent Form (ages 13-18)**,** and a Parent Form completed by caregivers of children aged 5-18 years**.**

In this study, children aged 10-12 years completed a 17-item child version of the PCSI, with responses recorded on a 3-point Likert scale (0 = *no*, 1 = *a little*, 2 = *a lot*). Items were written in child-friendly language (e.g., "Have you had headaches or has your head hurt?", "Have you felt dizzy, like things were spinning or moving?", and "Have you felt grumpy or irritable?").

Adolescents aged 13–19 years completed a 21-item version rated on a 7-point Likert-type scale ranging from 0 (*no problem)* to 6 (*severe problem)*, with 3 indicating a *moderate problem*. Participants were asked to rate the extent to which each symptom had been a problem for them the previous month. Items were introduced with the prompt "*Have you been experiencing any of the following over the last month?*" and assessed a range of post-concussion symptoms, including headache, nausea, balance problems, dizziness, visual problems (e.g., double vision or blurring), clumsiness, sensitivity to light and noise, irritability, sadness, nervousness, mental "fog", difficulty concentrating, difficulty remembering, confusion with directions or tasks, slowed response to questions, feelings of being slowed down, fatigue, drowsiness, and sleeping more than usual.

Parents or caregivers completed the 20-item Parent Form, rated on a 7-point Likert-type scale ranging from 0 (*no problem)* to 6 (*severe problem)*, with 3 indicating a *moderate*

problem. They rated how their child had felt over the past month (e.g., “Complained of headaches”, “Complained of nausea”, “Appeared dizzy or complained of dizziness”).

For the current study, total PCSI scores and subscale scores (physical, emotional, cognitive, and sleep/fatigue) were calculated according to the technical manual’s scoring procedures. Scores from the child self-report PCSI were converted to the 7-point rating scale used in the adolescent and parent forms to ensure comparability across age groups and enable analysis on a common metric.

Mean total scores were used as an index of overall symptom burden, while mean subscale scores allowed examination of domain-specific symptom patterns relevant to post-mTBI recovery. Mean scores were used rather than raw total scores because PCSI versions differ in the number of items across age groups, allowing scores from different forms to be compared within the same analyses.

The PCSI demonstrates strong psychometric properties across child, adolescent, and parent versions. Internal consistency for the clinical scales is robust, with Cronbach’s alpha values typically ranging from .86 to .95 across forms (Gioia et al., 2019). The measure shows strong test-retest reliability, particularly for total symptom scores, and displays good inter-rater agreement between parent and adolescent reports. Construct validity is well established: factor analyses support the four-domain structure, and PCSI scores reliably differentiate between concussed and non-injured youth, demonstrating strong discriminant validity (PCSI-2; Gioia et al., 2019).

The PCSI also demonstrates high sensitivity to changes in symptoms over time, making the measure appropriate for tracking recovery. Convergent validity has been shown through significant correlations with other established post-concussion symptom measures, while the manual reports clear evidence that PCSI symptom scores decrease in line with clinical recovery trajectories. Overall, the PCSI-2 is regarded as a psychometrically sound

instrument for assessing post-concussion symptoms in paediatric populations, supporting its use in both clinical and research settings (PCSI-2; Gioia et al., 2019).

Post-concussive symptoms (baseline severity). Pre-injury (baseline) parent-reported PCSI data were available from the CRANIAC dataset. Post-injury recovery can be assessed by calculating the difference between current and pre-injury PCSI ratings (the delta score).

Visual Perception Tasks

Participants completed two visual perception tasks: (1) the Ebbinghaus Illusion Task and (2) the Müller-Lyer Illusion Task. This study replicated the visual perception tasks developed by Sidhu (2024), using the same stimulus characteristics, task parameters, and administration procedures.

Ebbinghaus Illusion Task

In this task, two white target circles were shown side-by-side in the middle of a black background (Figure 1). On each trial, the targets appeared either with surrounding inducer circles (context condition) or without inducers (no-context condition). The targets were separated by a centre-to-centre distance of approximately 2.2 cm. In the context condition, one target was surrounded by six larger inducers (diameter: 2.5 cm) and the other by eight smaller inducers (diameter: 0.3 cm). The side on which the large or small inducers appeared was counterbalanced. Target circles could be the same size or differ slightly, with diameters of 1.3 cm, 1.5 cm or 1.7 cm. In trials of different sizes, the larger target could appear on either the left or the right. Participants responded via keyboard, pressing A to indicate that the stimuli were the same size and L to indicate that they were different sizes. Participants first completed six practice trials to familiarise themselves with the task. They then completed 56 trials (28 with context and 28 without context). Same-size and different-size pairings were

fully counterbalanced across trials, and all stimuli were presented in random order. Each display remained on the screen until a response was made.

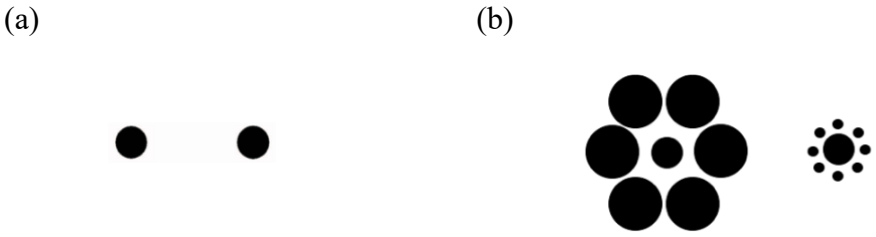


Figure 1.

Example stimuli from the Ebbinghaus task. Panel A shows a no-context trial in which the two target circles appear alone. Panel B shows a context trial in which each target is surrounded by either large or small inducer circles. The target circles are identical in size in both examples, but the presence of surrounding inducers typically alters perceived size.

Müller-Lyer Illusion task

In this task, two horizontal white lines were presented in the centre of a black background, one above the other (Figure 2). Lines were shown either with arrowheads (context condition) or without arrowheads (no-context condition). In the context condition, one line had inward-pointing arrowheads (> <), and the other had outward-pointing arrowheads (< >). The assignment of arrowhead type to the top or bottom line was counterbalanced.

Lines could be identical in length or differ slightly. Line lengths were 2.0 cm, 2.5 cm, and 3.0 cm, and in different-length trials, either line could appear as the longer one. The vertical distance between the two lines was approximately 1 cm**.** Participants responded using the keyboard, pressing A to indicate the stimuli were the same length and L to indicate they were different lengths. Participants completed six practice trials before beginning the main

task. The task included 42 experimental trials (28 context and 14 no-context), with all length combinations and arrowhead configurations presented in random order. Stimuli remained on screen until a response was recorded. For each participant, the number of correct responses was summed to obtain total scores, and percentage accuracy was calculated separately for context and no-context trials.

Figure 2.

Example stimuli from the Müller–Lyer task. Panel A shows a no-context trial with plain horizontal lines. Panel B shows a context trial in which each line is flanked by inward- or outward-pointing arrowheads. Although the two lines are physically equal in length, the arrowheads distort perceived length (Müller–Lyer illusion).

An optional visual-search task was included for engagement and was developed for this study. Participants viewed a series of 'Where's Kiwi?' images, each containing a hidden kiwi character embedded within a complex scene (Figure 3). On each trial, participants searched for the kiwi and responded by clicking directly on the target with the mouse. A correctly placed click within the predefined hit-box surrounding the character was recorded as a hit. If participants clicked elsewhere on the image or selected the on-screen option indicating that they could not find the kiwi, the response was recorded as a miss**.**

The task advanced automatically following each response, and no accuracy feedback was provided. Data from the 'Where's Kiwi?' task were not included in the present analysis because the task falls outside of the scope of this thesis.

Figure 3.

Example scene from the optional 'Where's Kiwi?' task, which was used for engagement only and is not analysed in this thesis.

Procedure

All interested participants were sent the Participant Information Sheet (PIS) and consent forms and were asked to complete a brief eligibility screening. Screening confirmed age eligibility, access to a computer with a keyboard, and eligibility criteria related to concussion history. Eligible participants were then scheduled for an assessment, which was conducted either in person (at either the University of Waikato Hamilton or Tauranga campus) or via Microsoft Teams. A reminder message/email was sent approximately 24 hours before the assessment. A Microsoft Teams link was sent 10 minutes before the scheduled assessment start time, and participants were instructed to access the session using a computer with a keyboard.

At the beginning of each assessment, the research assistant shared their screen while they reviewed and completed the PIS and consent/assent documents with the participant (and parent, where applicable) using the Qualtrics application. For remote assessments, both the participant and the research assistant had their cameras on during the process to facilitate joint review of information and address questions.

Participants aged 16 years or older provided verbal consent, while participants aged 10-15 years provided verbal assent alongside verbal parental consent. Participants were reminded that their participation was voluntary, that they could withdraw at any time, and that their data would be kept confidential.

Following consent/assent, demographic information and the PCSI were completed. For remote assessments, the research assistant read each item aloud and entered participants' verbal responses directly into Qualtrics, confirming each response before proceeding. The same procedure was used for in-person assessments.

Once the questionnaires were completed, participants were directed to the visual illusion tasks. For remote assessments, the research assistant emailed participants a link to the tasks and instructed them to open the link only when prompted, while in-person participants completed the tasks on a university computer with the link preloaded. Participants entered their participant ID to link task data with questionnaire responses.

Before starting the tasks, participants were asked to sit at a desk or table in front of a computer screen positioned at approximately arm's length and to remain seated and focused on the screen throughout task completion. For younger participants completing the assessment at home, parents were present but were asked not to assist with responses. A researcher remained on the Microsoft Teams call throughout the session to provide supervision and technical support as needed.

The task software automatically detected screen size and adjusted stimulus scaling accordingly. A brief welcome screen was then presented, followed by an overview of the task before practice trials began.

After participants completed the final task, a blank black screen appeared, indicating that the assessment was complete. The research assistant then checked in with the participant,

asked whether they had experienced any issues during the session, and provided an opportunity to ask questions. The participant's postal address was confirmed prior to sending the $20 Warehouse voucher. Sessions typically lasted between 30 and 60 minutes, depending on the participant's pace and whether they completed the optional 'Where's Kiwi' task. The research assistant thanked the participant and reminded them that they could withdraw their consent at any time within two weeks.

Data Analysis

Data analyses were conducted using IBM SPSS Statistics v. 31. Statistical significance was set at $\alpha = .05$ (two-tailed) for all analyses. Prior to hypothesis testing, data were screened for missing values, outliers, and distributional assumptions. There was minimal missing data across outcome variables. In the mTBI group, 1 participant (2.5%) was missing data for each outcome variable; in the comparison group, 2 participants (5.1%) were missing data. Given the small proportion of missing values, analyses were conducted using pairwise deletion.

Potential outliers were examined using boxplots. A small number of extreme values were observed; however, they were considered plausible given task performance and were not indicative of data-entry errors. All values were therefore retained for analysis.

Normality of the illusion task outcome variables was assessed using Shapiro–Wilk tests and visual examination of boxplots. Several variables showed significant departures from normality ($p < .05$), particularly for the Müller–Lyer task under both context and no-context conditions. As a result, non-parametric statistical procedures were used for all inferential analyses involving illusion task performance.

Accuracy on the visual illusion tasks was calculated as the proportion of correct responses for each participant in each condition (context and no-context) for both the Müller-

Lyer and Ebbinghaus tasks. Proportion-correct scores were calculated by dividing the number of correct responses by the total number of trials in each condition, with higher values indicating greater accuracy. Independent-samples *t*-tests were conducted to compare demographic characteristics between the mTBI and comparison groups.

Group differences in illusion task performance between adolescents with a history of mTBI and comparison participants were examined using Mann-Whitney *U* tests. These tests compared proportion-correct accuracy across illusion tasks under context and no-context conditions. Effect sizes were calculated using the rank-biserial correlation (*r*), derived from the standardised test statistic (*Z*), to estimate the magnitude of group differences.

Associations between age and illusion task performance were examined using Spearman's rank-order correlation coefficients (Spearman's ρ) across the full sample (mTBI and comparison participants combined), as preliminary analyses indicated no significant differences between groups. These analyses focused on performance under the context conditions for both the Müller-Lyer and Ebbinghaus tasks. To explore potential stage-related differences within adolescence, participants were grouped as younger (10–15 years) and older (16 years and above) adolescents according to the age ranges of the PCSI questionnaire versions. Exploratory non-parametric group comparisons were conducted between these age groups.

Spearman's rank-order correlations were conducted to examine whether time since injury (in months) was associated with illusion task performance within the mTBI group. Time since injury was correlated with proportion correct on context trials for the Müller–Lyer and Ebbinghaus illusion tasks.

Associations between post-concussion symptom burden and illusion task performance were examined within the mTBI group using Spearman's rank-order correlations. Illusion task accuracy under the context conditions was correlated with PCSI scores.

Both parent report and adolescent self-report versions of the PCSI were used in this study to assess symptom burden, including total mean symptom scores and mean subscale scores (physical, emotional, cognitive, and sleep/fatigue domains). Previous research has shown that parent and adolescent reports of post-concussion symptoms are significantly correlated, indicating modest agreement between informants; however, adolescents tend to report higher mean symptom severity than parents, particularly for somatic symptoms (Hajek et al., 2011; Talley, Hajek, Klamar, & Robinson, 2014). Using both adolescent and parent reports, therefore, allowed a more complete assessment of symptom burden following mTBI than relying on a single informant alone.

To examine symptom burden relative to pre-injury functioning, a delta PCSI score was calculated for the mTBI group by subtracting pre-injury parent-reported PCSI scores from current parent-reported PCSI scores. Negative values were set to zero, ensuring that higher scores indicated greater symptom burden above baseline. Child self-report PCSI scores were not used in delta score analyses due to the absence of pre-injury child self-report data.

Results

Concussion Symptom Burden

Current symptom severity for the mTBI and TBI-free comparison group is presented in Table 2. Independent-samples *t*-tests were conducted to compare current PCSI mean scores between the mTBI and comparison groups separately for parent and self-report measures. For the parent-report PCSI, the mTBI group reported significantly higher symptom severity on the Physical, Cognitive, Sleep and Total subscales. No significant group differences were observed for the Emotional subscale.

For the adolescent self-report PCSI, the mTBI group reported significantly higher symptom severity than the comparison group on the Physical subscale, the Cognitive subscale, and the total subscale score. No significant group differences were observed for the Emotional subscale or the Sleep subscale.

Overall, mean PCSI scores across parent- and self-report measures indicated low-to-mild current symptom severity in both the mTBI and comparison groups. Across symptom domains, ratings were generally highest for emotional and sleep symptoms, whereas physical and cognitive symptoms were comparatively lower. Although mean symptom scores tended to be higher in the mTBI group than in the comparison group, they remained within the low-to-mild range, reflecting a relatively modest symptom burden at the time of assessment.

Parent-reported delta PCSI scores were low overall, indicating minimal symptom elevation relative to pre-injury baseline at the time of assessment. The mean delta PCSI score was 0.25 (SD = 0.55), with scores ranging from 0.00 to 2.40. This pattern suggests that most participants reported little to no increase in symptoms relative to pre-injury, although a small number continued to report elevated symptoms.

Table 2

Current Post-Concussion Symptom Inventory (PCSI) Scores for Parent and Self Report for the mTBI and Comparison Group.

	Group				Test of significance
Domain	mTBI *M (SD)*		Comparison *M (SD)*		
Parent-Report (N=31)					
Physical	0.74	(0.91)	0.24	(0.32)	$t(41) = 2.56$, $p = .014$, $d = 0.79$
Emotional	1.60	(1.51)	1.03	(0.99)	$t(40) = 1.49$, $p = .145$, $d = 0.47$
Cognitive	1.28	(1.49)	0.54	(0.62)	$t(40) = 2.25$, $p = .030$, $d = 0.71$
Sleep	1.25	(1.73)	0.33	(0.44)	$t(40) = 2.56$, $p = .014$, $d = 0.81$
Total Score	1.24	(0.91)	0.93	(0.71)	$t(41) = 2.67$, $p = .011$, $d = 0.83$
Self-Report (N=77)					
Physical	1.19	(0.97)	0.53	(0.61)	$t(75) = 3.54$, $p < .001$, $d = 0.81$
Emotional	1.17	(1.59)	1.52	(1.48)	$t(75) = 0.48$, $p = .636$, $d = 0.11$
Cognitive	1.57	(1.36)	0.95	(1.01)	$t(75) = 2.27$, $p = .026$, $d = 0.52$
Sleep	1.57	(1.56)	0.96	(1.33)	$t(75) = 1.84$, $p = .070$, $d = 0.42$
Total Score	1.43	(1.80)	0.84	(0.75)	$t(75) = 2.79$, $p = .007$, $d = 0.64$

Note. PCSI = Post-Concussion Symptom Inventory. Higher scores indicate greater symptom severity. Test of significance values represents independent-samples *t*-tests comparing the mTBI and comparison groups. Effect sizes are reported as Cohen's *d*. Two-tailed *p* values are reported. $p < .05$ indicates statistical significance.

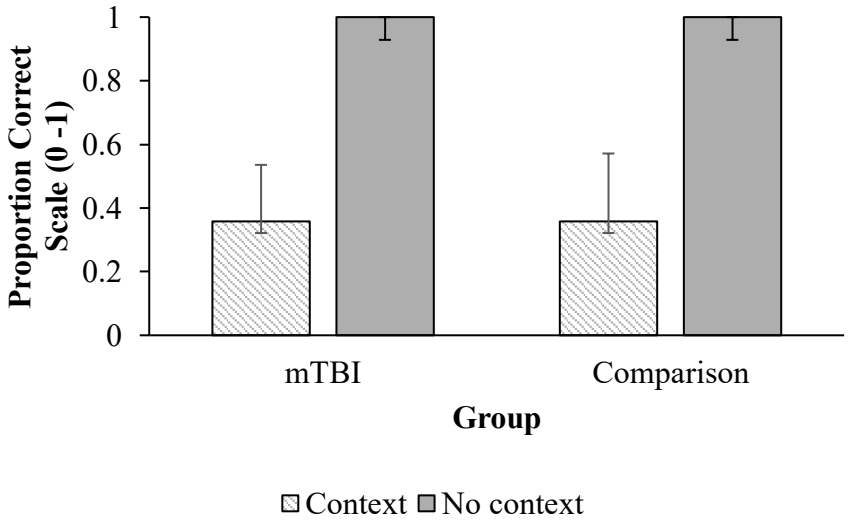
Visual Illusion Task Performance in Adolescents with and without mTBI

Mann–Whitney *U* tests were used to examine whether adolescents with a history of mTBI showed significantly different performance from comparison participants on illusion (context) trials. No significant differences were found on no-context trials, based on proportion correct scores.

For the Müller–Lyer task, there were no significant differences between the mTBI and comparison groups on either context trials, $U = 658.50$, $Z = -0.66$, $p = .509$, $r = .08$, or no-context trials, $U = 718.50$, $Z = -0.04$, $p = .968$, $r = .00$ (see Figure 4).

Figure 4.

Median Proportion Correct on the Müller-Lyer Illusion Task Under Context and No-Context Conditions for Adolescents with a History of mTBI and Comparison Participants.

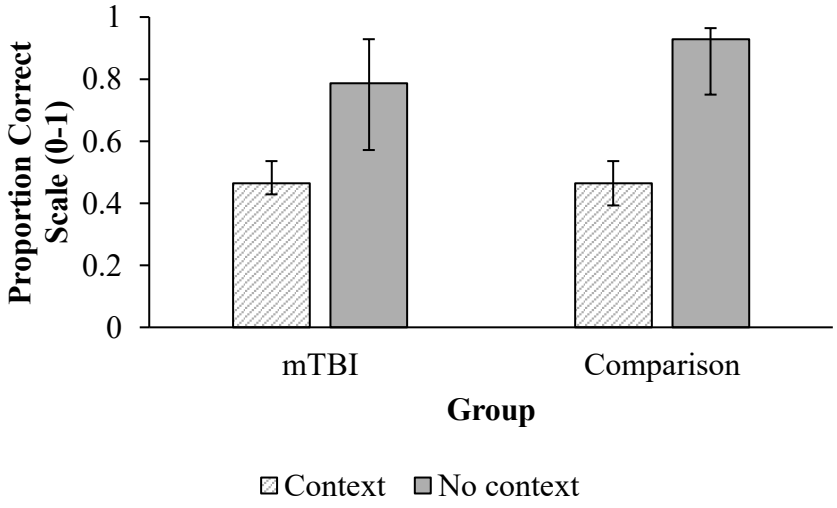


Note. Error bars represent interquartile ranges.

For the Ebbinghaus task, no significant group difference was observed on context trials, $U = 695.00$, $Z = -0.28$, $p = .782$, $r = .03$. In contrast, the mTBI group performed significantly less accurately than the comparison group on no-context trials, $U = 484.50$, $Z = -2.48$, $p = .013$, $r = .28$ (see Figure 5).

Figure 5.

Median Proportion Correct on the Ebbinghaus Illusion Task Under Context and No-Context Conditions for Adolescents with a History of mTBI and Comparison participants.



Note. Error bars represent interquartile ranges.

Age-Related Differences in Visual Illusion Task Performance

To examine whether age was associated with task performance, Spearman's rank-order correlations were conducted between participant age and proportion correct on context trials for the Müller–Lyer and Ebbinghaus tasks. As preliminary analyses indicated no significant differences in illusion task performance between the mTBI and comparison groups, the two groups were combined and analysed as a single sample. This approach

increased statistical power and enabled examination of age-related associations across the full range of participants.

Age was not significantly associated with Müller–Lyer context accuracy, r_s (76) = .17, p = .138, or Ebbinghaus context accuracy, r_s (76) = .11, p = .333. These findings indicate that illusion task performance did not vary significantly with age in the present sample. Scatterplots illustrating these associations are presented in Appendix A. Visual inspection of the plots indicated no clear linear relationship between age and performance for either task.

Exploratory comparisons between younger (ages 10-15) and older (16 and above) adolescents revealed a significant difference in Müller–Lyer no-context accuracy, with older adolescents performing more accurately than younger adolescents (U = 483.50, p = .046). No significant differences were observed for the remaining illusion conditions.

Associations Between Post-Concussion Symptoms and Visual Illusion Task Performance

To examine whether post-concussion symptom burden was associated with visual illusion task performance, Spearman's rank-order correlations were conducted within the mTBI group. Correlations were calculated between context-trial accuracy for the Müller–Lyer and Ebbinghaus illusions and PCSI subscale and total scores from parent-report and self-report measures (see Table 3).

For the parent-reported PCSI, no significant associations were observed between Müller–Lyer context accuracy and physical, emotional, cognitive, sleep, or total symptom severity (all ps > .05). Similarly, Ebbinghaus context accuracy was not significantly associated with any parent-reported symptom domain or total score (all ps > .05).

For the adolescent self-report PCSI, no significant correlations were observed between illusion-context accuracy and any symptom subscale or total score for either the

Müller–Lyer or Ebbinghaus tasks (all ps > .05). This indicates that adolescent-reported symptom burden was not associated with performance on either visual-illusion task.

Table 3

Spearman Correlations Between Post-Concussion Symptoms and Visual Illusion Task Performance (mTBI group)

Variable	N	ML context accuracy (ρ)	EB context accuracy (ρ)
Parent-Report			
Physical symptoms	18	−.29	.33
Emotional symptoms	17	−.34	.03
Cognitive symptoms	17	−.03	.04
Sleep symptoms	17	−.01	.18
Total symptoms	18	−.24	.23
Self-Report			
Physical symptoms	38	−.16	.06
Emotional symptoms	38	−.17	.10
Cognitive symptoms	38	−.26	−.13
Sleep symptoms	38	−.09	−.05
Total symptoms	38	−.19	.01

Note. Values represent Spearman's rho (ρ) correlations. Analyses include only participants with a history of mTBI. ML = Müller–Lyer illusion; EB = Ebbinghaus illusion. Higher symptom scores indicate greater symptom severity.

Spearman's rank-order correlations were conducted to examine whether time since injury was associated with illusion task performance within the mTBI group. Time since injury was not significantly correlated with Müller–Lyer context accuracy, r_s (39) = .03, p = .851, or Ebbinghaus context accuracy, r_s (39) = .08, = .635. These findings indicate that illusion task performance did not vary significantly as a function of time elapsed since injury.

Discussion

Overview of findings

The current study investigated whether adolescents with a history of mTBI differed from the TBI-free comparison group in susceptibility to two visual illusions (Müller–Lyer and Ebbinghaus), whether illusion performance varied with age across adolescence, and whether post-concussion symptom burden was associated with illusion performance in the mTBI group. These aims were grounded in evidence that paediatric mTBI outcomes are heterogeneous (Bodien et al., 2023; Maas et al., 2022) and that common clinical tools may not detect subtle disruptions in brain function, particularly when conventional imaging is normal, and symptoms have improved (Haste et al., 2025; Konigs et al., 2015; Silverberg et al., 2020).

Findings did not support hypothesis 1: Adolescents with a history of mTBI did not show reduced susceptibility on contextual (illusion) trials relative to comparison participants for either the Müller–Lyer or Ebbinghaus tasks. This differs from Sidhu's (2024) findings. Sidhu's adult mTBI sample showed reduced susceptibility to both illusions, interpreted as reduced global integration and weaker use of contextual cues, an effect consistent with dorsal-stream vulnerability following mTBI (Alnawmasi et al., 2022; Sidhu, 2024).

In contrast, adolescents in the present study performed similarly to controls on context trials. One key difference between the present findings and those reported by Sidhu (2024) and colleagues lies in the time since injury. Participants in Sidhu's (2024) study were assessed within the first 12 months following mTBI, whereas adolescents in the present sample were assessed, on average, 2.3 years post-injury and reported relatively low levels of current symptoms. Therefore, any early disruption to perceptual processing may have resolved by the time of assessment in the present study. This interpretation is consistent with

typical recovery trajectories reported in paediatric mTBI, where many individuals show substantial symptom improvement over time (Gudymenko et al., 2025).

mTBI may also have different effects on visual-perceptual processing in developing adolescents compared with adults. However, further research is needed to determine whether developmental differences in post-injury perceptual outcomes are reliably observed across visual tasks.

Despite the absence of overall group differences in contextual illusion susceptibility, one specific performance difference was observed. The only clear group difference emerged in the Ebbinghaus no-context condition, where the mTBI group showed poorer accuracy than controls. Across participants, performance in the no-context condition was also lower overall for the Ebbinghaus task than for the Müller–Lyer task, suggesting that the Ebbinghaus discrimination trials were more difficult, whereas Müller–Lyer no-context trials were relatively easier. Paired comparisons confirmed a significant difference between illusion types in the no-context condition, with higher accuracy for Müller–Lyer than Ebbinghaus trials.

This effect did not match the predicted pattern (i.e., a difference only on context trials), suggesting that for some adolescents, a history of mTBI may relate to broader perceptual or attentional factors (e.g., discrimination consistency when contextual cues are reduced), rather than to a selective impairment in contextual integration. This interpretation is compatible with the view that mTBI can disrupt multiple functional systems and produce subtle effects that may not be detected by global outcome measures (Bodien et al., 2023), particularly when conventional imaging appears normal (Konigs et al., 2015; Haste et al., 2025). This also aligns with research showing that objective perceptual measures may reveal functional differences not apparent from symptoms alone (Silverberg et al., 2020; Kamins et al., 2017).

In addition to examining group differences, the study also investigated whether illusion susceptibility varied with age. Age was not significantly associated with susceptibility to either the Müller–Lyer or Ebbinghaus illusions in either group. This finding differs from much developmental research reporting age-related changes in illusion susceptibility across childhood. However, evidence is not entirely consistent. In their systematic review of *The Development of Susceptibility to Geometric Visual Illusions in Children*, Wincza et al. (2024) reported substantial variability in developmental trajectories across illusion types and study designs.

For the Müller–Lyer illusion, many studies report decreasing susceptibility with age (e.g., Brosvic et al., 2002; Dawson et al., 1973; Porac & Coren, 1981), suggesting reduced illusion magnitude across development. However, some studies have reported minimal or no age-related differences (e.g., Tinker, 1938; Cretenoud et al., 2020), while others have found task- or stimulus-dependent effects (e.g., Pollack, 1970).

Developmental findings for the Ebbinghaus illusion are similarly variable but often show the opposite pattern, with susceptibility increasing with age (e.g., Doherty et al., 2010; Bremner et al., 2016; Imada et al., 2013). Nevertheless, several studies report no developmental differences (e.g., Hanisch et al., 2001; Duemmler et al., 2008), or effects that depend on specific stimulus characteristics (e.g., Hadad, 2018; Coren & Porac, 1978).

Together, these findings indicate that developmental changes in illusion susceptibility are not uniform and may depend on the specific perceptual task and methodological approach used. One explanation for the absence of age effects in the present study may be the relatively narrow age range of the sample, which primarily comprised adolescents who may have already reached a more mature stage of visual integration. Many studies detecting developmental change include younger children (aged 5 – 10) across broader age ranges, suggesting that the most pronounced developmental differences occur earlier in childhood

and may stabilise by adolescence (Brosvic et al., 2002; Mavridis et al., 2020; Schulze et al., 2022). Although age was not linearly associated with illusion performance, exploratory analyses indicated that adolescents (16+ years) performed more accurately than younger (10 – 15 years) on Müller–Lyer no-context trials. This finding suggests that developmental differences may reflect stage-related changes rather than continuous linear change across age.

The study also examined whether current symptom burden was associated with illusion performance. Hypothesis 3 was not supported. Within the mTBI group, neither parent-reported nor adolescent self-reported symptom severity was significantly associated with context trial accuracy for either illusion task. These findings suggest that current symptom burden was not reliably related to contextual visual processing performance in this sample.

Interpretation of the parent-report findings should be made cautiously, given the relatively small number of parents who provided symptom data. Participation in parent-report measures may have been influenced by symptom severity, such that parents of adolescents with more noticeable or persistent symptoms were more likely to complete questionnaires. This potential selection bias may limit the representativeness of the parent-report data and reduce confidence in conclusions regarding symptom–performance relationships.

Current symptom severity in the mTBI group was generally low to mild at the time of assessment, and participants were assessed, on average, approximately 2.3 years post-injury. This suggests that many individuals may have experienced substantial recovery by the time of testing. As a result, overall symptom levels were relatively modest, with limited variability across participants. This restricted range of symptom severity may have reduced the likelihood of detecting strong or consistent associations between current symptom burden and illusion task performance. These findings should therefore be interpreted in the context of a

sample characterised by relatively mild ongoing symptoms and a considerable period of recovery since injury.

Overall, the findings extend the literature by using visual illusion tasks to assess an adolescent sample, addressing a gap noted in concussion research, which has historically focused on adolescents and adults in sport contexts (Davis et al., 2017; Santana et al., 2026). Although the predicted reduction in contextual susceptibility observed in adults (Sidhu, 2024) was not replicated in adolescents, the results still support the rationale that objective perceptual tasks can provide information beyond symptom checklists (Silverberg et al., 2020; Kamins et al., 2017). Notably, the pattern suggests that developmental stage may shape how mTBI-related perceptual differences manifest, reinforcing the need for developmentally informed assessment approaches (Braddick & Atkinson, 2011; Duemmler et al., 2008; Wincza et al., 2024).

Finally, interpretation of perceptual findings must be considered in the context of the sample's symptom profile. Across PCSI versions, current symptom severity was generally low to mild in both groups, although the mTBI group reported significantly higher symptoms on several physical and cognitive domains in parent- and adolescent-report measures. This pattern is consistent with the broader literature showing that many children recover within weeks while a subset experience ongoing symptoms (Barlow et al., 2021; Zemek et al., 2016). This also aligns with research emphasising that symptom profiles in paediatric mTBI are variable and influenced by developmental and contextual factors (Bodien et al., 2023; Russell et al., 2017; Zemek et al., 2016).

Although symptom levels were generally low to mild at the time of testing, adolescents with a history of mTBI reported higher symptom burden than comparison participants in some domains, and their delta scores indicated that symptoms had not fully returned to pre-injury baseline levels. At the same time, symptoms were also reported by

participants without a history of mTBI, highlighting that many concussion-like symptoms occur in everyday life and are not specific to injury. This underscores the importance of including comparison groups in concussion research and, where possible, obtaining pre-injury symptom reports to accurately interpret post-injury symptom change.

Strengths

A key strength of the present study is its focus on addressing a clear gap in the literature by using visual illusions to assess paediatric mTBI. Concussion research has often prioritised adolescent and adult sport-related samples, with few studies on younger populations and developmentally sensitive perceptual outcomes (Davis et al., 2017; Santana et al., 2026). By using objective perceptual tasks, the study complements symptom-based measures and responds to concerns that symptom checklists alone may not capture subtle functional disruption or delayed recovery processes (Silverberg et al., 2020; Kamins et al., 2017).

The inclusion of children and adolescents allowed examination of age-related patterns in illusion performance, which is particularly relevant given that higher-order visual integration continues to mature across childhood and adolescence (Braddick & Atkinson, 2011; Wincza et al., 2024). In addition, the inclusion of a comparison group enabled evaluation of whether performance patterns were specific to mTBI history, extending adult findings in this area to a developmental sample (Sidhu, 2024). Finally, integrating perceptual task performance with symptom measures is an initial step toward understanding whether objective perceptual functioning relates to clinically used indicators of recovery in paediatric mTBI (Gioia et al., 2009; Silverberg et al., 2020).

Limitations

Several limitations should be considered when interpreting these findings. First, statistical power was limited, which may have reduced sensitivity to detect small group differences in illusion susceptibility. This is particularly relevant given the heterogeneity of paediatric mTBI and the likelihood that perceptual effects may be subtle (Bodien et al., 2023; Maas et al., 2022). Relatedly, the generalisability of results may be limited by sample characteristics (e.g., recruitment source, injury history variability). The sample spanned a relatively adolescent age range but did not include younger children, limiting the ability to capture earlier developmental transitions in perceptual processing. (Santana et al., 2026; Zemek et al., 2016).

Secondly, methodological factors may have influenced task performance. Remote testing may introduce variability in lighting, distraction, and fatigue, which could affect perceptual accuracy. Additionally, symptom assessment relied on self- and proxy-report, which can be influenced by recall accuracy, developmental differences in symptom insight, and contextual pressures (Russell et al., 2017; Meier et al., 2015).

Finally, the study may have been limited by the range of injury recency. Adult findings by Sidhu (2024) were based on mTBI within the previous 12 months, whereas participants in the present sample were assessed, on average, more than two years post-injury. This extended time since injury exceeds typical recovery timeframes reported for paediatric mTBI, where most children show substantial symptom resolution within 2-4 weeks following injury (Silverberg et al., 2020). Consistent with this, participants in the present study reported relatively low levels of current symptoms, suggesting that many may have been in a later stage of recovery at the time of assessment. Including more participants with recent injury may therefore be important for detecting group differences in perceptual

functioning, particularly if perceptual disruptions are most evident earlier in recovery and diminish over time.

Future research

Future research should build on the current findings by examining visual-illusion susceptibility across a broader age range and at earlier post-injury stages. Including participants closer to the time of injury may help clarify whether perceptual differences are more apparent during the acute or subacute phases of recovery. In addition, extending sampling to include younger children, particularly those under 10 years of age, would enable clearer investigation of developmental trajectories in visual integration. A broader age range would help determine whether age-related patterns in illusion susceptibility emerge earlier in development and may have been less detectable in the predominantly adolescent sample examined here.

Longitudinal designs are needed to better characterise recovery over time following paediatric mTBI. Tracking individuals from the acute phase through later stages of recovery would allow researchers to examine how changes in visual perception relate to symptom resolution, functional outcomes, and return to school or sport. Such designs would also help determine whether alterations in illusion susceptibility reflect transient disruption or longer-lasting changes in perceptual processing.

Notably, ongoing research within the broader concussion study from which the current sample was drawn is examining adolescents with more recent mTBI. These data will provide an opportunity to assess visual perception closer to the time of injury, when physiological disruption may be greatest, and to evaluate whether illusion susceptibility is more sensitive during the acute or subacute phases of recovery. Comparing performance

across different post-injury time points may clarify the temporal relationship between symptom improvement and perceptual recovery.

Future studies should also continue to integrate objective perceptual tasks with standard clinical assessments. Combining visual illusion paradigms with symptom measures may improve the sensitivity of concussion assessment by capturing subtle functional changes that are not evident solely through symptom reporting. Together, this line of research has the potential to inform the development of more objective, developmentally appropriate tools for assessing recovery following paediatric mTBI.

Conclusion

In summary, the present study examined visual illusion susceptibility in adolescents with a history of mTBI and TBI-free comparison groups, as well as associations with age and post-concussion symptom burden. No significant group differences were observed on context trial task performance, and age was not associated with illusion susceptibility within the sample. Symptom burden was not associated with task performance.

Overall, these findings indicate that contextual visual processing appears comparable between adolescents with and without mTBI at the time of assessment, while highlighting the importance of age and time since injury when investigating subtle perceptual outcomes following paediatric concussion.

References

Accident Compensation Corporation. (2026). *Sport Concussion in New Zealand: National Guidelines*. https://www.acc.co.nz/assets/Uploads/National-concussion-guidelines-v4.pdf

Alnawmasi, M. M., Mani, R., & Khuu, S. K. (2022). Changes in the components of visual attention following traumatic brain injury: A systematic review and meta-analysis. *PLoS ONE, 17*(6), e026895. https://doi.org/10.1371/journal.pone.0268951

Armstrong, R. A. (2018). Visual problems associated with traumatic brain injury. *Clinical and Experimental Optometry, 101*(6), 716-726. https://doi.org/10.1111/cxo.12670

Barlow, K. M., Kirk, V., Brooks, B., Esser, M. J., Yeates, K. O., Zemek, R., . . . Dewey, D. (2021). Efficacy of Melatonin for Sleep Disturbance in Children with Persistent Post-Concussion Symptoms: Secondary Analysis of a Randomized Controlled Trial. *Journal of Neurotrauma, 38*(8), 950-959. https://doi.org/10.1089/neu.2020.7154

Bodien, Y. G., Barber, J., Taylor, S. R., Boase, K., Corrigan, J. D., Dikmen, S., . . . Giacino, J. T. (2023). Feasibility and Utility of a Flexible Outcome Assessment Battery for Longitudinal Traumatic Brain Injury Research: A TRACK-TBI Study. *Journal of Neurotrauma, 40*(3-4), 337-348. https://doi.org/10.1089/neu.2022.0141

Braddick, O., & Atkinson, J. (2011). Development of human visual function. *Vision research, 51*(13), 1588-1609. https://doi.org/10.1016/j.visres.2011.02.018

Brain Injury Association of New Zealand. (n.d.). *What is brain injury?* https://www.brain-injury.org.nz

Bremner, A. J., Doherty, M. J., Caparos, S., de Fockert, J., Linnell, K. J., & Davidoff, J. (2016). Effects of Culture and the Urban Environment on the Development of the Ebbinghaus Illusion. *Child development, 87*(3), 962-981. https://doi.org/10.1111/cdev.12511

Brosvic, G. M., Dihoff, R. E., & Fama, J. (2002). Age-Related Susceptibility to the Müller-Lyer and the Horizontal-Vertical Illusions. *Perceptual and Motor Skills, 94*(1), 229-234. https://doi.org/10.2466/pms.2002.94.1.229

Buhagiar, F., Fitzgerald, M., Bell, J., Allanson, F., & Pestell, C. (2020). Neuromodulation for Mild Traumatic Brain Injury Rehabilitation: A Systematic Review. *Frontiers in Human Neuroscience, 14*, 598208. https://doi.org/10.3389/fnhum.2020.598208

Chadwick, L., Sharma, M. J., Madigan, S., Callahan, B. L., & Yeates, K.O. (2022). Classification Criteria and Rates of Persistent Postconcussive Symptoms in Children: A Systematic Review and Meta-Analysis. *The Journal of Pediatrics, 246*, 131-137.e132. https://doi.org/10.1016/j.jpeds.2022.03.039

Chan, Y., Thorne, P. R., & Taylor, R. L. (2025). Self-reported dizziness, balance, and multisensory impairment following mild traumatic brain injury: An exploratory study. *Journal of the Royal Society of New Zealand, 55*(3), 451-465. https://doi.org/10.1080/03036758.2024.2412095

Coren, S., & Girgus, J. (2020). *Seeing is Deceiving: The Psychology of Visual Illusions*. Routledge.

Coren, S., & Porac, C. (1978). Iris Pigmentation and Visual-Geometric Illusions. *Perception, 7*(4), 473-477. https://doi.org/10.1068/p070473

Cretenoud, A. F., Grzeczkowski, L., Bertamini, M., & Herzog, M. H. (2020). Individual differences in the Müller-Lyer and Ponzo illusions are stable across different contexts. *Journal of Vision, 20*(6), 4-14. https://doi.org/10.1167/jov.20.6.4

Davis, G. A., Anderson, V., Babl, F. E., Gioia, G. A., Giza, C. C., Meehan, W., . . . Zemek, R. (2017). What is the difference in concussion management in children as compared with adults? A systematic review. In *British Journal of Sports Medicine,* 51, 949-957. https://doi.org/10.1136/bjsports-2016-097415

Dawson, J. L. M., Young, B. M., & Choi, P. P. C. (1973). Developmental Influences on Geometric Illusion Susceptibility among Hong Kong Chinese Children. *Journal of Cross-cultural Psychology, 4*(1), 49-74. https://doi.org/10.1177/002202217300400105

Ditzinger, T. (2021). *Illusions of Seeing: Exploring the World of Visual Perception*. Springer.

Doherty, M. J., Campbell, N. M., Tsuji, H., & Phillips, W. A. (2010). The Ebbinghaus illusion deceives adults but not young children. *Developmental Science, 13*(5), 714-721. https://doi.org/10.1111/j.1467-7687.2009.00931.x

Duemmler, T., Franz, V. H., Jovanovic, B., & Schwarzer, G. (2008). Effects of the Ebbinghaus illusion on children's perception and grasping. *Experimental Brain Research, 186*, 249-260. https://doi.org/10.1007/s00221-007-1229-0

Gentaz, E., & Hatwell, Y. (2004). Geometrical haptic illusions: The role of exploration in the Müller-Lyer, vertical-horizontal, and Delboeuf illusions. *Psychonomic bulletin & Review, 11*(1), 31-40. https://doi.org/10.1007/s00221-007-1229-0. https://doi.org/10.3758/BF03206457

Ginsburg, J., & Smith, T. (2025). Traumatic Brain Injury. In *StatPearls*. StatPearls Publishing.

Gioia, G. A., Schneider, J. C., Vaughan, C. G., & Isquith, P. K. (2009). Which symptom assessments and approaches are uniquely appropriate for paediatric concussion? *British Journal of Sports Medicine, 43*(Suppl 1), i13-i22. https://doi.org/10.1136/bjsm.2009.058255

Gioia, G. A., Schneider, J. C., Vaughan, C. G., & Isquith, P. K. (2019). *Post-Concussion Symptom Inventory–2 (PCSI-2).* Psychological Assessment Resources.

Gudymenko, A., Iuliano, S. G., Gagnon, I. J., Iverson, G. L., Cook, N. E., Zemek, R., & Teel, E. F. (2025). Mechanism of Injury and Clinical Recovery Outcomes Following Pediatric Concussion. *Journal of Neurotrauma, 42*(17-18), 1631-1640. https://doi.org/10.1089/neu.2024.0483

Haas, R., Zayat, M., & Sevrin, A. (2019). Current Concepts in the Evaluation of the Pediatric Patient with Concussion. *Current Reviews in Musculoskeletal Medicine, 12*(3), 340-345. https://doi.org/10.1007/s12178-019-09561-7

Hadad, B. S. (2018). Developmental trends in susceptibility to perceptual illusions: Not all illusions are created equal. *Attention, Perception & Psychophysics, 80*(6), 1619-1628. https://doi.org/10.3758/s13414-018-1529-4

Hajek, C. A., Yeates, K. O., Taylor, H. G., Bangert, B., Dietrich, A., Nuss, K. E., . . . Wright, M. (2011). Agreement between Parents and Children on Ratings of Post-Concussive Symptoms Following Mild Traumatic Brain Injury. *Child neuropsychology, 17*(1), 17-33. https://doi.org/10.1080/09297049.2010.495058

Hanisch, C., Konczak, J., & Dohle, C. (2001). The effect of the Ebbinghaus illusion on grasping behaviour of children. *Experimental Brain Research, 137*(2), 237-245. https://doi.org/10.1007/s002210000655

Hansen, C. R., Teramoto, M., Gardner, J., & Vaughan, C. (2023). Evidence for the Validation of a Single Item Recovery Question (SIRQ) in Children With Mild and Complicated Mild Traumatic Brain Injury. *Pediatric Neurology, 142*, 16-22. https://doi.org/10.1016/j.pediatrneurol.2023.02.001

Haste, P., de Almeida e Bueno, L., Jérusalem, A., & Bergmann, J. (2025). Performance of current tools used for on-the-day assessment and diagnosis of mild traumatic brain injury in sport: A systematic review. *British Journal of Sports Medicine, 11*(1), e001904. https://doi.org/10.1136/bmjsem-2024-001904

Heyer, G. L., Schaffer, C. E., Rose, S. C., Young, J. A., McNally, K. A., & Fischer, A. N. (2016). Specific Factors Influence Postconcussion Symptom Duration among Youth Referred to a Sports Concussion Clinic. *The Journal of Pediatrics, 174*, 33-38.e32. https://doi.org/10.1016/j.jpeds.2016.03.014

Howe, C. Q., & Purves, D. (2005). The Müller-Lyer Illusion Explained by the Statistics of Image-Source Relationships. *Proceedings of the National Academy of Sciences, 102*(4), 1234-1239. https:/ doi.org/10.1073/pnas.0409314102

Imada, T., Carlson, S. M., & Itakura, S. (2013). East-West cultural differences in context-sensitivity are evident in early childhood. *Developmental Science, 16*(2), 198-208. https:/ doi.org/10.1111/desc.12016

James, S. L., Theadom, A., Ellenbogen, R. G., Bannick, M. S., Montjoy-Venning, W., Lucchesi, L. R., . . . Murray, C. J. L. (2019). Global, regional, and national burden of traumatic brain injury and spinal cord injury, 1990 –2016: A systematic analysis for the Global Burden of Disease Study 2016. *The Lancet Neurology, 18*(1), 56-87. https:/ doi.org/10.1016/S1474-4422(18)30415-0

Jha, S., & Ghewade, P. (2022). Management and Treatment of Traumatic Brain Injuries. *Cureus, 14* 10). https:/ doi.org/10.7759/cureus.30617

Kamins, J., Bigler, E., Covassin, T., Henry, L., Kemp, S., Leddy, J. J., . . . Giza, C. C. (2017). What is the physiological time to recovery after concussion? A systematic review. *British Journal of Sports Medicine*, *51*(12), 935-940. https://doi.org/10.1136/bjsports-2016-097464

Kids Health. (2024). *Caring For Your Child After A Head Injury.* https://www.kidshealth.org.nz/first-aid/caring-for-your-child-after-a-head-injury

Kirsch, W., & Kunde, W. (2021). On the origin of the Ebbinghaus illusion: The role of figural extent and spatial frequency of stimuli. *Vision Research, 188*, 193-201. https://doi.org/10.1016/j.visres.2021.07.016

Konigs, M., Weeda, W. D., van Heurn, L. W., Vermeulen, R. J., Goslings, J. C., Luitse, J. S., . . . Oosterlaan, J. (2015). Impaired Visual Integration in Children with Traumatic Brain Injury: An Observational Study. *PLoS one, 10*(12), e0144395. https://doi.org/10.1371/journal.pone.0144395

Leddy, J. J., Haider, M. N., Noble, J. M., Rieger, B., Flanagan, S., McPherson, J. I., . . . Willer, B. (2021). Clinical Assessment of Concussion and Persistent Post-Concussive Symptoms for Neurologists. *Current Neurology and Neuroscience Reports, 21*(12), 70. https://doi.org/10.1007/s11910-021-01159-2

Maas, A. I. R., Menon, D. K., Manley, G. T., Abrams, M., Åkerlund, C., Andelic, N., . . . Zemek, R. (2022). Traumatic brain injury: progress and challenges in prevention, clinical care, and research. The *Lancet Neurology, 21*(11), 1004-1060. https://doi.org/10.1016/S1474-4422(22)00309-X

Marzolla, M. C., Resch, C., Hurks, P., Schepers, J., Borghans, L., Rietman, A., . . . & Renaud, I. (2025). Sensory processing patterns in pediatric mild traumatic brain injury: A longitudinal study. *Applied Neuropsychology. Child*, 1-10. https://doi.org/10.1080/21622965.2025.2549930

Mavridis, P., Kärtner, J., Cavalcante, L. I. C., Resende, B., Schuhmacher, N., & Köster, M. (2020). The Development of Context-Sensitive Attention in Urban and Rural Brazil. *Frontiers in psychology, 11*, 1623. https://doi.org/10.3389/fpsyg.2020.01623

Mavroudis, I., Ciobica, A., Bejenariu, A. C., Dobrin, R. P., Apostu, M., Dobrin, I., & Balmus, I.-M. (2024). Cognitive Impairment following Mild Traumatic Brain Injury (mTBI): A Review. *Medicina, 60*(3), 380. https://doi.org/10.3390/medicina60030380

McCrory, P., Meeuwisse, W. H., Aubry, M., Cantu, R. C., Dvořák, J. í., Echemendia, R. J., . . . Turner, M. (2013). Consensus Statement on Concussion in Sport—The 4th International Conference on Concussion in Sport Held in Zurich, November 2012. *PM & R, 5*(4), 255-279. https://doi.org/10.1016/j.pmrj.2013.02.012

McInnes, K., Friesen, C. L., MacKenzie, D. E., Westwood, D. A., & Boe, S. G. (2017). Mild Traumatic Brain Injury (mTBI) and chronic cognitive impairment: A scoping review. *PLoS One, 12*(4), e0174847. https://doi.org/10.1371/journal.pone.0174847

McMahon, P. J., Hricik, A., Yue, J. K., Puccio, A. M., Inoue, T., Lingsma, H. F., . . . & Vassar, M. J. (2014). Symptomatology and Functional Outcome in Mild Traumatic Brain Injury: Results from the Prospective TRACK-TBI Study. *Journal of Neurotrauma, 31*(1), 26-33. https://doi.org/10.1089/neu.2013.2984

Meier, T. B., Brummel, B. J., Singh, R., Nerio, C. J., Polanski, D. W., & Bellgowan, P. S. F. (2015). The underreporting of self-reported symptoms following sports-related concussion. *Journal of Science and Medicine in Sport, 18*(5), 507-511. https://doi.org/10.1016/j.jsams.2014.07.008

Nwafor, D. C., Brichacek, A. L., Foster, C. H., Lucke-Wold, B. P., Ali, A., Colantonio, M. A., . . . & Qaiser, R. (2022). Pediatric Traumatic Brain Injury: An Update on Preclinical Models, Clinical Biomarkers, and the Implications of Cerebrovascular Dysfunction. *Journal of Central Nervous System Disease, 14*, https://doi.org/10.1177/11795735221098125

Philipson, E. B., Gause, E., Conrick, K. M., Erickson, S., Muma, A., Liu, Z., . . . & Vavilala, M. S. (2021). Concussion symptoms and temporary accommodations using a student-centered return to learn care plan. *NeuroRehabilitation, 49*(4), 655-662. https://doi.org/10.3233/NRE-210182

Pollack, R. H. (1970). Mueller-Lyer Illusion: Effect of Age, Lightness Contrast, and Hue. *Science, 170*(3953), 93-95. https://doi.org/10.1126/science.170.3953.93

Porac, C., & Coren, S. (1981). Life-span trends in the perception of the Mueller-Lyer: Additional evidence for the existence of two illusions. *Canadian journal of psychology, 35*(1), 58-62. https://doi.org/10.1037/h0081127

Roberts, B., Harris, M. G., & Yates, T. A. (2005). The Roles of Inducer Size and Distance in the Ebbinghaus Illusion (Titchener Circles). *Perception, 34*(7), 847-856. https://doi.org/10.1068/p5273

Russell, K., Selci, E., Chu, S., Fineblit, S., Ritchie, L., & Ellis, M. J. (2017). Longitudinal Assessment of Health-Related Quality of Life following Adolescent Sports-Related Concussion. *Journal of Neurotrauma, 34*(13), 2147-2153. https://doi.org/10.1089/neu.2016.4704

Santana, J., Padilla, A. N., Wren, T. A. L., Vue, Y., & Hamilton, A. (2026). Pediatric concussion characteristics differ based on age. *Brain Injury, 40*(2), 75-81. https://doi.org/10.1080/02699052.2025.2582153

Schulze, C., Buttelmann, D., Zhu, L., & Saalbach, H. (2022). Context-Sensitivity Influences German and Chinese Preschoolers' Comprehension of Indirect Communication. *Journal of cross-cultural psychology, 53*(10), 1257-1276. https://doi.org/10.1177/00220221221104952

Shvedoff, T. (2025). Mild Traumatic Brain Injury: Reviewing Current Trends in Neuroimaging & Biomarkers. https://doi.org/10.58445/rars.3022

Sidhu, A. (2024). *Reduced global processing bias in people with a history of mild traumatic brain injury: Grass everywhere and not a field in sight.* The University of Waikato.

Silverberg, N. D., Iaccarino, M. A., Panenka, W. J., Iverson, G. L., McCulloch, K. L., Dams-O'Connor, K., . . . & Weyer Jamora, C. (2020). Management of Concussion and Mild Traumatic Brain Injury: A Synthesis of Practice Guidelines. *Archives of physical medicine and rehabilitation, 101*(2), 382-393. https://doi.org/10.1016/j.apmr.2019.10.179

Starship. (2024). *Concussion Returning to School*. https://media.starship.org.nz/return-to-school-after-concussion-advice - sheet/Concussion_Returning_to_School__Dec_2024.pdf

Talley, R. D., Hajek, C., Klamar, K., & Robinson, K. (2014). Poster 561 Parent-Child Agreement on Post-Concussive Symptoms following Mild Traumatic Brain Injury. *PM & R, 6*, S381-S381. https://doi.org/10.1016/j.pmrj.2014.08.920

Teel, E. F., Zemek, R. L., Tang, K., Gioia, G., Vaughan, C., Sady, M., & Gagnon, I. J. (2019). The Stability of Retrospective Pre-injury Symptom Ratings Following Pediatric Concussion. *Frontiers in Neurology, 10*, 672-672. https://doi.org/10.3389/fneur.2019.00672

Thorstensen, J., Godfrey, H., King, R., Zewdie, E., Kirton, A., Yeates, K. O., . . . & Barlow, K. (2026). Repetitive Transcranial Magnetic Stimulation in Adolescents With Persistent Postconcussion Symptoms After Mild Traumatic Brain Injury: An Open Label Safety and Feasibility Study. *Pediatric Neurology, 175*, 198-207. https://doi.org/10.1016/j.pediatrneurol.2025.11.015

Tinker, M. A. (1938). Susceptibility to Optical Illusions: Specific or General? *Journal of Experimental Psychology, 22*(1), 593. https://doi.org/10.1037/h0062463

Todorović, D. (2020). What Are Visual Illusions? *Perception, 49*(11), 1128-1199. https://doi.org/10.1177/0301006620962279

Tomaiuolo, R., Zibetti, M., Di Resta, C., & Banfi, G. (2023). Challenges of the Effectiveness of Traumatic Brain Injuries Biomarkers in the Sports-Related Context. *Journal of Clinical Medicine, 12*(7), 2563. https://doi.org/10.3390/jcm12072563

Tuersunjiang, T., Wang, Q., Yang, H., Gao, F., & Wang, Z. (2025). Long-term effects of mild traumatic brain injury in pediatrics. *Acta psychologica, 258*, 105260. https://doi.org/10.1016/j.actpsy.2025.105260

Wait, T. J., Eck, A. G., Loose, T., Drumm, A., Kolaczko, J. G., Stevanovic, O., & Boublik, M. (2023). Median Time to Return to Sports After Concussion Is Within 21 Days in 80% of Published Studies. *Arthroscopy, 39*(3), 887-901. https://doi.org/10.1016/j.arthro.2022.11.029

Wincza, R., Hartley, C., Fenton-Romdhani, J., Linkenauger, S., & Crawford, T. (2024). The development of susceptibility to geometric visual illusions in children – A systematic review. *Cognitive Development, 69*, 101410. https://doi.org/10.1016/j.cogdev.2023.101410

Zavagno, D. (2023). Illusion as a Cognitive Clash Rooted in Perception. *Journal of Intelligence, 11*(11), 215. https://doi.org/10.3390/jintelligence11110215

Zemek, R., Barrowman, N., Freedman, S. B., Gravel, J., Gagnon, I., McGahern, C., . . . & Beer, D. (2016). Clinical risk score for persistent postconcussion symptoms among children with acute concussion in the ED. *JAMA, 315*10), 1014-1025. https://doi.org/10.1001/jama.2016.1203

Appendix A

Scatterplots of Age and Illusion Context Accuracy

Figure A1

Association Between Age and Müller–Lyer Context Accuracy

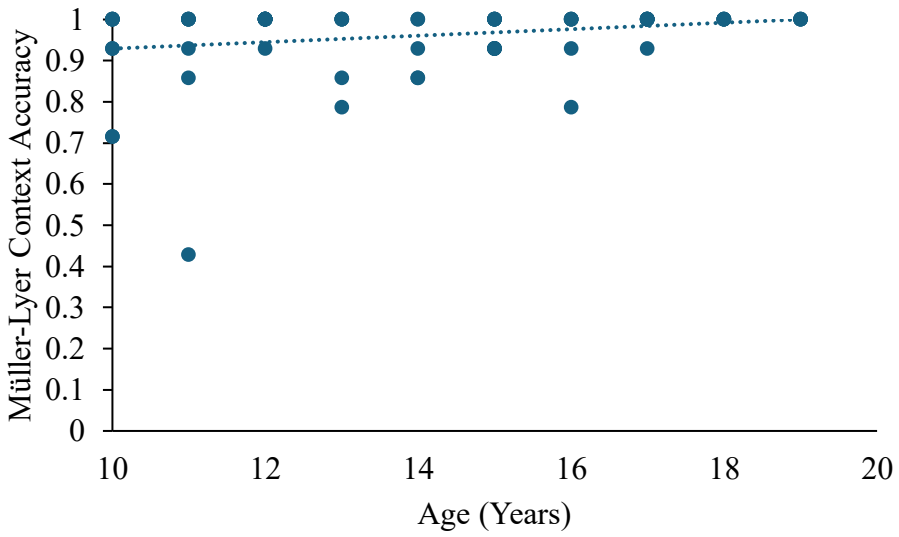
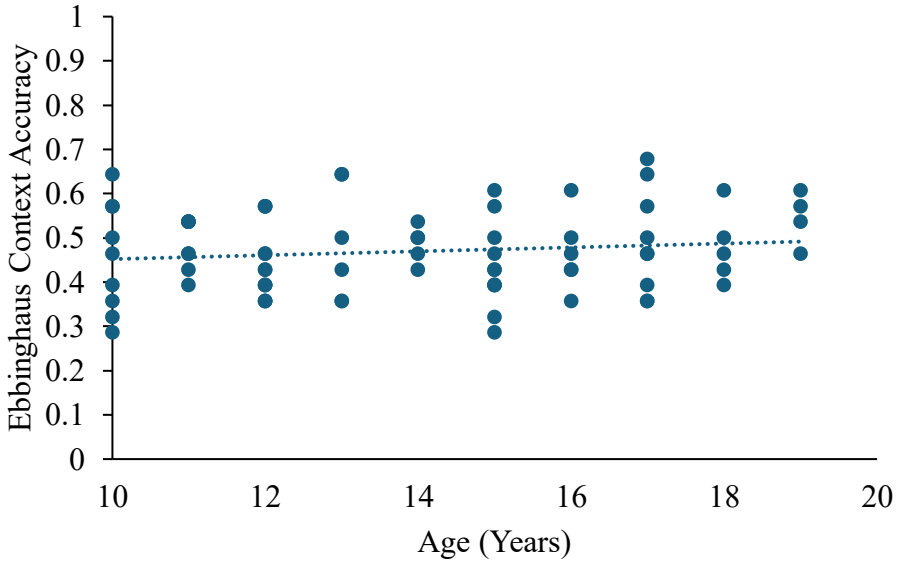


Figure A2

Association Between Age and Ebbinghaus Context Accuracy



Note. Points represent individual participants. The dotted line represents the linear trend. Analyses include the full sample (mTBI and comparison groups combined).

Appendix B

Information and Consent Sheets

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

THE UNIVERSITY OF WAIKATO
Visual perception after mild TBI in children and adolescents

Parent or Guardian (under 16) Participant Information Sheet

What is the study about?

Concussion (mild traumatic brain injury – mTBI) is a common injury in children and young people, but it is very difficult to know when they are fully recovered – we cannot 'see' a concussion on x-ray like we can a broken bone.

Currently recovery is assessed by self-report – we ask children and their parents to rate the severity of various symptoms. However, the brain might not be fully recovered even when someone feels better and is symptom free.

We want to find out if visual illusion / visual perception tasks can detect mTBI/concussion in young people and see if we can use them to assess recovery. A lot of the neural pathways in the brain are involved in vision and are vulnerable to damage after concussion or mTBI.

We are looking for young people **with a history of concussion (part of the CRANIAC study), as well as young people without a history of concussion/mTBI (and their parents) to take part in** the study. We will compare the outcomes from visual perception and visual illusion tasks to see if there are differences between the two groups.

The study is being led by Professor Nicola Starkey, with Professor Rich Masters, Dr Mitchell Head (University of Waikato), Associate Professor Kelly Jones (AUT University) and Dr Amanpreet Sidhu (University of the Fraser Valley, Canada) and Masters student Emily Cliff.

Am I eligible to take part?

We are looking for two groups of **young people aged 10-19 years** and their parents to take part

1. Those *with concussion/mTBI in the last three years* (you were part of the CRANIAC study) *and*
2. Young people *who have never had a concussion or mTBI*

Families can participate in person (at the University) or online at home if you have a computer/laptop with a keyboard and access to zoom or teams and a camera.

What am I being asked to do?

A researcher will contact you to explain the study to you, what you'll be expected to do and answer any questions you might have. If you want to take part your child will be asked to complete three online tasks that involve them i) answering some questions about concussion related symptoms, ii) judging the size of objects on a series of different displays and iii) finding cartoon characters as quickly as they can in various scenes.

We will also ask you to complete a short demographic questionnaire, and rate their concussion like symptoms. The session will take no more than an hour and you will receive a $20 Warehouse voucher as a thank you. Your participation is voluntary (your choice).

What will happen to my information?

The information you provide will be anonymous (we will give you a unique ID number). All paper forms will be stored in a locked cabinet, in the School of Psychology at Waikato University. The electronic data will be stored in a password protected folder on the University of Waikato OneDrive. At the end of the study the paper-based forms will be destroyed. We will send an electronic summary of the findings to participants who have indicated they would like to receive this information.

The study findings may be written up for publication as part of a conference presentation or journal article and Master thesis.

What are the possible benefits and risks of this study?

Taking part in this study will take some of your time. There are no known risk caused by this study. This study will be of benefit to the wider population but may not directly

benefit you. The results obtained from your participation will help us find out if we can use visual perception tasks to assess recovery from concussion.

What can I expect from the researchers?
If you decide to participate in this project, the researchers will respect your right to:

- ask any questions of the researchers about the study at any time during participation;
- decline to answer any particular questions;
- withdraw from the study within 2 weeks of the study session;
- provide information on the understanding that it is confidential to the researchers. All forms are identified by a code number, and are only seen by the researchers. It will not be possible to identify you in any articles produced from the study.
- be given an electronic summary of the findings

Who can I speak with about my participation in this project?

- If you, or anyone you know is interested in taking part in this research please contact Sade Lomas on **concussion@waikato.ac.nz** for further information or ring/text 022 015 9773

This research project has been approved by the Human Research Ethics Committee (Health) at the University of Waikato as HREC(Health)2025#48. Any questions or concerns about the ethical conduct of this research may be sent to the Secretary of the Committee, email humanethics@waikato.ac.nz, postal address, Human Research Ethics Committee (Health), University of Waikato, Te Whare Wananga o Waikato, Private Bag 3105, Hamilton 3240.