USING EYE-TRACKING TECHNOLOGY AS A MEASURE OF COGNITION IN TRAUMATIC BRAIN INJURY: A SCOPING REVIEW

by

Hilary Catherine Pearson

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Dalhousie University is located in Mi'kma'ki,
the ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

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ABSTRACT

Cognitive impairment is a common and debilitating symptom of mild traumatic brain injury (mTBI). Conventional neuropsychological assessment tools rely on verbal or manual responses, and there is no universally accepted protocol. Current methods are sensitive to extraneous factors such as stress, intelligence, and motivation, suggesting the need for more objective tools. A scoping review was undertaken to explore the utility of eye-tracking methods for detecting cognitive impairment in mTBI patients, and to survey the kinds of tasks used in this context. Six academic databases were searched for studies related to brain injury, eye tracking, and cognition. Data from 19 articles were extracted and synthesized. In most cases, neuropsychological and eye-tracking methods were in accordance when detecting cognitive impairment. In many cases, eye tracking measures detected impairments when neuropsychological tasks did not. This review suggests that eye tracking could provide an effective, objective method to measure cognitive impairment in mTBI.

LIST OF ABBREVIATIONS USED

CT	Computed topography
CPT	Continuous performance test
DAI	Diffuse axonal injury
dlPFC	Dorsolateral prefrontal cortex
DTI	Diffusion tensor imaging
EOG	Electrooculography
GCS	Glasgow coma scale
ICP	Intracranial pressure
LOC	Loss of consciousness
MRI	Magnetic resonance imaging
mTBI	Mild traumatic brain injury
ONSD	Optic nerve sheath diameter
PTSD	Post traumatic stress disorder
PTA	Post traumatic amnesia
TBI	Traumatic brain injury
VOG	Video oculography

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CHAPTER 1 - INTRODUCTION

The Centers for Disease Control and Prevention defines a traumatic brain injury (TBI) as a bump, blow, or jolt to the head or a penetrating head injury that disrupts the normal function of the brain (Langlois et al., 2006). Traumatic brain injury is a serious public health issue. In the US alone, an estimated 1.7 million people sustain a TBI annually. Of those cases, 275,000 require hospitalization and 58,000 die (Faul et al., 2010). The statistics for Canada are similar with an annual rate of 500 per 100,000 individuals. This is equivalent to 456 cases a day or an injury every 3 minutes (Brain Injury Statistics in Canada, n.d). Globally, the annual estimated incidence of TBI is 27 million cases (Global Burden of Disease Contributors, 2016). These estimates are thought to be conservative due to the high rate of underreporting (Kroshus et al., 2015; Wallace et al., 2015).

Traumatic brain injury affects vulnerable populations disproportionately, exponentially increasing the complexity of care. Rates of TBI are highest in the 75 years old and above age group (2,232.2 per 100,000 population), along with high rates of TBI-related hospitalizations driven primarily by falls. In 2013, falls were the leading cause of TBI, accounting for 47.2% of all TBIs in the United States. Other common mechanisms of injury included by being struck by or against an object (15.4%) and motor vehicle crashes (13.7%) (Taylor et al., 2017). The second most affected age group was 0-4 years (1,591.5 per 100,000). Accordingly, in 2012, approximately 430,000 emergency department visits resulted from sports and recreation related mTBI and nearly 70% of those ED visits occurred among individuals aged 0-19 years. The rate of sports related concussion has been steadily increasing in the last decade (Coronado et al., 2015).

Injury Severity

There is a high level of heterogeneity within the assessment, symptomology, and recovery of TBI. These factors are influenced by many factors including the severity of the injury. Although there are several tools utilized for the classification of TBI, the most widely used is the Glasgow Coma Scale (GCS). This clinical scale allows measurement of consciousness after a brain injury based on three categories: eye opening, verbal response, and motor response (Teasdale & Jennet, 1974). These sub-scores are added together to create a final score ranging from 3-15. A score of 13-15 indicates mild injury, 9-12 indicates moderate, and 8 or less indicates severe injury. Most brain injuries are of mild severity level, comprising 70-90% of all cases (Cassidy et al., 2004). Pupil reactivity was later added as a subscale to reflect brainstem function, graded on a scale of 0-2 (both eyes, one eye, or no reactivity). The combination of the GCS and the pupil score has been denoted GCS-P and is calculated by subtracting the pupil score from the total GCS score (Brennan, et al., 2018). Another assessment tool, more commonly used in research settings, is the Abbreviated Injury Scale (AIS). This is a scale of mortality from 1 (minor injury) to 6 (non-survivable injury) (Frieden et al., 2015). Other indicators of injury severity include loss of consciousness (LOC), duration of posttraumatic amnesia (PTA), duration of alteration of consciousness and neuroimaging findings (Brasure et al., 2012). The American Congress of Rehabilitation Medicine defines a mild traumatic brain injury (mTBI) as PTA no greater than 24 hours and LOC no greater than 30 minutes (Kay et al., 1993).

Pathology

Another common feature of mTBI is the lack of visible intracranial pathology. Conventional imaging methods such as computed topography (CT) and magnetic resonance imaging (MRI) typically reveal no abnormalities (Rees, 2003). This is because the damage occurs on a microscopic neural tissue level, a phenomenon called diffuse axonal injury (DAI). DAI is caused by shearing forces which lead to white matter tracts being stretched and pulled apart (Mesfin et al., 2021; Smith et al., 2003). The most common mechanism involves linear acceleration of the head. When the skull is rapidly accelerated or decelerated, like in a motor vehicle accident, the brain lags behind because of its own inertia. This displacement of the brain leads to shearing effects (Hardy et al., 2007; Smith et al., 2003). This same scenario can also lead to focal brain damage as the brain collides with the skull, leading to a contusion. Coup contusions occur at the site of impact and contrecoup contusions occur directly opposite the site of impact. Therefore, even focal damage can be induced in the absence of physical impact (Hardy et al., 2007). Diffuse axonal injuries and contusions are considered intra-axial because they involve the brain parenchyma. Extra-axial injuries occur within the skull but don't involve the brain parenchyma; these include epidural hematoma, subdural hematoma, subarachnoid hemorrhage, and intraventricular hemorrhage (McKee & Daneshvar, 2015).

Symptomology

There is a very high level of heterogeneity of symptoms following mTBI. These patients commonly suffer from physical, cognitive, psychiatric, and ocular symptoms. Physical symptoms include headache, fatigue, dizziness, sleep disturbances, vertigo, balance, and gait abnormalities. Symptoms typically occur in the early stages and can resolve as early as 1-2 weeks (Yang et al., 2007) or up to 3 months (Dikmen et al., 2010; Kashluba et al., 2004). Cognitive impairment, however, has been reported to persist long term, sometimes greater than a year post injury (McInnes et al., 2017). These changes include memory problems, trouble concentrating, increased distractibility, and an inability to pay attention or solve problems (Carroll et al., 2004).

A less studied area of post-TBI symptomology is the secondary psychiatric consequences. Psychiatric disorders reported to develop after a TBI are post-traumatic stress disorder (PTSD), major depressive disorder, generalized anxiety disorder, obsessive compulsive disorder and panic disorder, and increased risk of suicide (Madsen et al., 2018; Mallya et al., 2015). Bombardier and colleagues (2010) found that over half of individuals in the first year of TBI met criteria for major depressive disorder.

Patients with mTBI can also present with ocular symptoms. Common ocular problems include accommodative insufficiency, deficits of saccades, photophobia, strabismus/cranial nerve palsies, reduced colour vision, dry eyes, and convergence insufficiency (Armstrong, 2018; Ciuffreda et al., 2007). The interaction of the different domains of symptoms complicates assessment further. For example, if someone complains of difficulty reading at near, the problem could be due to impaired concentration/attention or from convergence insufficiency or from decreased visual acuity (from dry eye, accommodative insufficiency, etc.). Because of the various areas of symptoms, there are an abundance of methods for assessing TBI.

Neuropsychology: assessment of cognitive function

Neuropsychology is a discipline within psychology that studies the relationship between cognitive processing and the corresponding neuroanatomy (Bilder, 2011).

Because patients present with a myriad of cognitive changes such as forgetfulness, confusion, and distractibility (Carroll et al., 2004), neuropsychological testing has become a popular method of assessment. Such assessments can provide valuable information about working memory, inhibitory control, and attentional mechanisms, all of which impact an individual's everyday life. To assess these cognitive domains, a neuropsychological battery is administered. The assessments included in the battery vary based on the cognitive deficit of interest. Common computerized neuropsychological assessments designed for brain injury include ImPACT (immediate post-concussion assessment and cognitive testing), Cogsport, and Headminder (Schatz & Zillmer, 2010). These assessments are typically used as preliminary screening tools for cognitive impairment and not to determine specific cognitive deficits (Haas et al., 2019). Self-report questionnaires are frequently administered to assess symptoms in mTBI patients. Some widely used questionnaires include the Sport Concussion Assessment Tool (SCAT), the Neurobehavioral Symptom Inventory, and the Rivermead Post Concussion Questionnaire (Polinder et al., 2018). Additionally, clinical interviews are often conducted; this includes reviewing medical records and interviews with family members (Podell et al., 2010).

Complexity of Assessment

These methods are extremely valuable to screen patients for cognitive deficits that interfere with everyday functioning. However, each of the previously mentioned methods come with limitations. Neuropsychological tests can be confounded by premorbid learning difficulties, external factors such as stress, pain and mood disturbances, and fatigue (Millis & Volinsky, 2001; Rees, 2003). Another factor that contributes to the complexity of assessment is the issue of incentives for performing well or poorly.

Possible motivation for overreporting of symptoms could be financial compensation in the form of health or workplace insurance. Thus, it would be valuable to have an assessment method that functions as a biomarker, an objective and quantifiable indicator of the medical state or disease observed from outside the patient (Strimbu & Tavel, 2011). This would allow assessment independent of patient report and still isolate genuine cognitive deficits and improve diagnostic accuracy.

Conversely, underreporting of symptoms is also a serious concern. Wallace and colleagues (2017) found that 55% of high school athletes did not report their concussion. One of the most common reasons for not reporting was not wanting to miss play time. Additionally, Kroshus et al., (2015) found that more than a quarter of their sample experienced pressure from teammates, coaches, and parents to continue playing. These influences could lead individuals to under-report symptoms on self-questionnaires and neuropsychological measures may not be sensitive enough to pick up deficits indicative of these ongoing symptoms (Coldren et al., 2012). This leads to individuals continuing to play with a pre-existing head injury which may be exacerbated by successive concussions. This concept is termed second impact syndrome, which can lead to diffuse cerebral swelling, brain herniation, and sometimes death (Cantu & Gean, 2010; Fisher & Vaca, 2004). Kroshus et al., (2015) found that almost half of the participants in their sample continued to play in games or practices while experiencing post-impact symptoms of a possible concussion. These high rates of underreporting of mTBI highlights the need for a more objective assessment method. This could prevent second impact syndrome and other possible fatal outcomes. Alternatively, some patients may underreport symptoms unintentionally. Studies have indicated that individuals with TBI underestimate the severity of their cognitive and behavioural impairments compared to ratings of family members, clinician ratings, and performance on neuropsychological testing (Flashman & McAllister, 2002).

Financial gain, competitive sport influences/pressures, and lack of perception of own symptoms, are only a few factors that contribute to the complexity of assessment of TBI. Another complicating factor of the assessment of brain injury is the lack of baseline data. This weakens the ability to draw confident conclusions that the deficit being examined is caused solely by the brain injury and not pre-existing factors. Interestingly, even this approach can be skewed by athletes deliberately underperforming on baseline assessment. Athletes motivated to continue playing in the event of an injury may do this in the hopes that the actual deficit will then be undetectable since the baseline was artificially low. This is sometimes referred to as "sandbagging" and is a known phenomenon in the athletic community (Gaudet & Weyandt, 2016).

Innovative Methods

The myriad of limitations of existing tools for cognitive assessment have prompted researchers to investigate new methods to assess status. To avoid these drawbacks, there has been an emphasis on methods that may function as biomarker. Serum biomarkers such as S100B, tau proteins, serum potassium, glucose, or white blood cell count and autoantibodies against glutamate are being actively studied. To date, there is no clear validated relation to injury severity (Lumba-Brown et al., 2018). Additionally, the invasive nature of these biomarkers limits their use as they are usually found in the cerebral spinal fluid or brain tissue itself (Friere-Aragon et al., 2017).

Increased intracranial pressure (ICP) is a neurophysiologic change that can occur from head trauma and can also be measured via the cerebral spinal fluid. A relatively novel method has emerged as a less invasive means to measure ICP as a proxy for TBI. This method uses an ultrasound or other imaging method to measure optic nerve sheath diameter (ONSD). When intracranial pressure raises, cerebral spinal fluid fills the cavity between the optic nerve and optic nerve sheath resulting in an increase in ONSD (Dubourg et al., 2011). This could be a promising method for severe and moderate brain injuries in which increased ICP is well documented but there is very limited research demonstrating increased ICP in mild traumatic brain injuries (Haider et al., 2018).

Considering the insensitivity of CT/MRI to mild brain injuries, attention has been turned to advanced neuroimaging techniques such as diffusion tensor imaging (DTI). DTI is a form of magnetic resonance imaging that provides information about the diffusion of water molecules in white matter tracts (McKee & Daneshvar, 2015). Unfortunately, all the aforementioned methods require trained professionals and expert viewer to interpret the results. Many also require highly invasive techniques or have not been extensively studied.

There is no single assessment tool that can capture the multidimensional nature of mTBI. Among the various assessment methods, cognitive evaluations have been the most commonplace. This is likely because performance on neuropsychological assessments have been found to be a good predictor of ability of functional status, return to work and productive activity (Pedone et al., 2005; Podell et al., 2010). Moreover, cognitive status has been found to be correlated to global outcome measures such as Glasgow Outcome Scale (GOS-E) (Bagiella et al., 2010; Wilson et al., 2000).

Cognition

The domains of cognition typically affected by mTBI include attention, processing speed, episodic and working memory, functional communication, and executive function. Deficits in attention make common skills such as multitasking difficult. Slowed processing speed can make an ordinary conversation difficult as the time it takes to produce a response is delayed. Furthermore, these individuals have difficulty understanding figurative language and sarcasm. Deficits in executive function sometimes present as difficulty planning, and impaired judgement. For example, they may have difficulty organizing their thoughts or prioritizing tasks leading to confusion and irritation (Carroll et al., 2004). Impaired judgment may be exhibited by inappropriate reactions to social situations, due to their inability to interpret the actions of others. Given the severe interruption to everyday functioning and therefore quality of life, cognitive deficits are one of the most important complications of brain injury (Mitchell et al., 2010).

The suitability of cognitive assessment tools varies with injury severity and stage of recovery. Brief batteries are often used for patients with severe TBI or in the acute period to avoid fatigue or floor effects (Podell et al., 2010). Emergency department and acute medical setting assessments include Galveston Orientation and Amnesia Test (GOAT) (Levin et al., 1979), Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005) and Mini-Mental State Exam (Folstein, 1975). More comprehensive formal testing is undertaken within a post-acute or outpatient setting. There is a plethora of assessments within each cognitive domain. For example, to measure executive function, Stroop Colour Word task and Trail Making Task are often used, and for memory California Verbal Learning Test (CVLT-II) or Rey Auditory Verbal Learning. Attention is often measured though continuous performance tasks or subcategories of Weschler Adult Intelligence Scale such as Digit Span and Letter-Number sequencing (Ganti et al., 2016; Podell et al., 2010).

Considering the significant burden of cognitive deficits for patients with mTBI, neuropsychological testing has been a leading tool in assessment. Like other kinds of assessments, there are limitations that accompany these methods. As previously mentioned, several external factors can confound the results of neuropsychological testing. Some of these factors can be controlled for such as age, exercise, diet (Pinella, 2006). More complex factors include effort/motivation, fatigue, pain, and litigation status. Co-morbidities such as depression, PTSD, substance abuse, premorbid intelligence, and psychiatric status can also influence the results. (Mallya et al., 2015; Millis & Volinsky, 2001; Podell et al., 2010).

Eye Tracking

Oculomotor testing has been gaining traction as a method capable of overcoming some of the previously mentioned limitations of existing assessment tools. Eye tracking has proved to be useful in a variety of contexts such as marketing, experimental psychology, and assistive technology (Carter & Luke, 2020). Gaze behaviour gives insight to how stimuli are processed on a moment-to-moment basis rather than just the final outcome. This allows for analysis of the way the information is processed. For example, instead of simply measuring reaction time on a cognitive task, the gaze behaviours lend insight to the strategies employed to complete the task. Eye movement patterns are sometimes deemed the ‘window to the mind’ as they can demonstrate unconscious processing. For example, it’s been found that while solving language puzzles, aphasia patients fixate the correct solution longer, but subsequently fail the task (Bridgeman, 1992). These findings suggest that eye movements are more automatic and/or function independent of manual or verbal responses. Hence making them more difficult to manipulate. This dissociation of eye movements patterns from behavioural performance has also been identified in individuals with dyslexia, autism (Bridgeman, 1992; Cooper et al., 2017) and healthy adults feigning cognitive impairment (Kanser et al., 2020).

Eye Movements

When looking directly at a stimulus, the image falls on the fovea, the area of the retina that provides the highest acuity vision. This structure is quite small, so only a small portion of the visual field is seen in high acuity vision. Therefore, an individual needs to move their eyes around to observe the whole scene. Pausing to view a stimulus positions the image onto the fovea, this is called a fixation (Cassin, 1995). To move a new target onto the fovea, fast conjugate ballistic eye movements called saccades, are initiated. To track a slow but smooth moving object, slower following movements called pursuits are activated. Fixations, saccades, and pursuit can be used to characterize how an individual processes a scene. For example, dwell time, and areas of interest describe the amount of time and areas that were fixated in a scene, respectively. These indices are thought to reflect underlying cognitive processes related to attention, perception, and decision-making (Majaranta & Bulling, 2014). For instance, fixation patterns in individuals with autism demonstrate less fixations to the eye area, suggesting a basis for altered social interaction (Boraston & Blakemore, 2007).

Neuroanatomy of eye movement systems

The neural processing networks responsible for generating eye movements overlap with many of the networks responsible for the kinds of cognitive functions that are often impaired in mTBI (Diwakar et al., 2015; Ting et al., 2016). Reflexive saccades originate in the parietal eye field within the posterior parietal cortex, and voluntary saccades originate in the frontal eye field in the frontal cortex. Other subcortical brain areas involved in saccadic pathway include the thalamus, basal ganglia, and superior colliculus (Cassin, 1995). Important brain areas for the production of smooth pursuit include the middle temporal area and medial superior temporal area (Pierrot-Deseilligny et al., 2004). The frontotemporal, and middle temporal lobe are especially susceptible to traumatic brain damage due to their proximity to boney protuberances within the skull. This susceptibility is hypothesized to be the basis of the core neurocognitive symptoms experienced from TBI (Bigler, 2007). Brain areas involved in cognitive aspects of saccade control are the dorsolateral prefrontal cortex (dlPFC) and the anterior cingulate gyrus. The latter is involved in modulation of voluntary saccades and the former is involved in inhibition of saccades. Inhibition of saccades is important in paradigms such as the anti-saccade task. In this task, participants are instructed to make a saccade in the opposite direction of the target. This requires the participant to suppress the pre-potent response to saccade on the target. Lesions in dlPFC have been associated with markedly increased error rate (Gaymard et al., 1998). There is a clear relationship between eye movement neural circuity, and brain areas involved with cognitive impairment. Thus, oculomotor testing could provide a method of assessing the same neuroanatomy involved in mTBI without the influence of extraneous factors.

Eye movement measurement

Eye movements can be measured clinically or with the use of eye tracking technology. Clinical assessment of eye movements requires a trained professional and even then, is subject to judgment and measurement error. Inter-rater reliability of these exams may suffer due to differing experience levels, knowledge levels and specialties. For example, the oculomotor exam may differ significantly between an ophthalmologist, neurologist, or emergency physician. Also, subtle deficits such as mild undershoot (hypometria) or overshoots (hypermetria) can be difficult to detect with the naked eye. (Anderson & MacAskill, 2013). Additionally, clinical assessment would not be sensitive to fine details such as change in latency. As technology advances, there has been a trend from manual to computerized eye tracking methods.

Eye tracking technology techniques can be divided into two main categories: electromagnetic and video based. Most early models were the former, including scleral search coil techniques and electrooculography (EOG). With the scleral coil technique, a contact lens or annulus with a copper wire embedded in it, is placed on the eye after being anesthetized. The participant is seated within a structure that generates a magnetic field. The movement of a copper wire in a magnetic field induces a voltage to be produced in the coil. The position of the eye can be determined by the amplitude of current in the coil (Singh & Singh, 2012). This method allows for high spatial and temporal resolution, high sampling rate and measurement of torsional eye movements. However, this method is invasive as the insertion of the contact lens can be uncomfortable and could even cause corneal abrasions if not inserted by a trained professional (Klaib et al., 2021).

EOG is derived from the principle that there is a difference in electrical potential between the front and back of the eye. With this dipole model, the cornea is considered the positive pole and the retina the negative pole. Micro-currents flow radially from the eye through the orbital tissue and surrounding skin. Electrodes are typically placed around the eye to pick up the standing potential generated. Electrodes are typically placed at the lateral and nasal canthi (for horizontal eye movements) and a ground electrode on the forehead. If the eyes move from the center position towards one of the electrodes, the retina approaches this electrode, while the cornea approaches the opposing one. The change in dipole direction causes a change in the electric potential field, which in turn can be measured to track eye movements (Singh & Singh, 2012). A significant advantage of this method is that it is not dependent or disturbed by lighting conditions. Sleep research often implements this method because it can be used in total darkness or even when the eyes are closed. This method is, however, prone to artifacts like signal noise and drifting (Klaib et al., 2021; Majaranta & Bulling, 2014).

Video oculography (VOG) is the most widely used approach consisting of a video camera that records the movements of the eyes and a computer that saves and analyses the data (Klaib et al., 2021). VOG may use either static or mobile eye trackers. Static eye tracker involves a more laboratory-based setting with the participant seated in front of a monitor presenting the stimuli. Static eye trackers may be subdivided into tower-mounted or remote. Tower-mounted eye trackers come in close contact with the eye(s) while with remote eye trackers the camera is set up near the monitor (stimulus) and view the eye from a distance (Holmqvist et al., 2011). Head stabilization techniques such as a bite bar or a chin/forehead rest are often used. Recently, mobile head-mounted devices such as glasses or helmets have been used to simulate a more real-life experience (Scott et al., 2019). Having head position fixed or loose raises the concept of gaze tracking versus eye tracking. The former refers to rotations of the eye with respect to a reference point in the environment, so a measurement of the eyes and head. Head mounted devices employ this technique. To determine the specific line of sight within the environment the head must be stabilized as with desktop eye trackers. This allows for direct measurement of gaze tracking, meaning a measurement of solely the eyes position within the head (Khan & Lee, 2019).

VOG can use either visible or infrared light. Visible light-based techniques locate the eye in the camera image by a specific eye region such as the limbus, iris or via blink detection. Visible light methods tend to be inaccurate and sensitive to head movement (Khan & Lee, 2019; Majaranta & Bulling, 2014). To address this problem, infrared light sources create a corneal reflection that remains at a fixed position on the eye. This system also uses a reference point such as the limbus (junction of the sclera and iris), center of the pupil or pupil/ iris junction. Gaze direction is then calculated by comparing the corneal light reflection to the moving reference point (i.e., center of pupil) (Majaranta & Bulling, 2014). The signal for vertical eye movements may be degraded as the lids may occlude the limbus. Lighting conditions need to be controlled as this method does not function well in ambient lighting. To avoid this, it is ideal to use a space with little to no windows to avoid direct or ambient light. Using lighting that emits minimal infrared light such as fluorescent or neon light is useful. Incandescent and halogen bulbs are best to avoid for this reason (Holmqvist et al., 2011).

The prevalence of eye tracking technology in research is exponentially growing. The automaticity of eye movements provides insight to underlying cognitive processing even beyond conscious control. Eye tracking is a compelling measurement tool for cognition due to its objectivity. This concept of using eye tracking to assess cognition is not a novel one. The basic premise of a saccade has been suggested to be cognitive in nature. Animal electrophysiological studies have found that it only takes around 60ms for the entire process of signalled and producing a saccade. Notwithstanding, the typical latency of a reflexive saccade is 200ms and varies (Carpenter & Williams, 1995). This discrepancy in time is thought to be due to decisional processes such as cost benefit analysis of whether the saccade is worth the processing resources. The process of looking towards a target – prosaccade- is frequently manipulated in the literature to measure various areas of cognition. These manipulations often involve a more cognitively taxing element. Examples include cueing, delayed target signalling and memorizing target location (Hutton, 2008).

Simply a natural viewing scene contains far too much information for our limited cognitive systems to process simultaneously. Therefore, selective attention is necessary to focus on the regions with the most relevant information. This principle has prompted an abundance of research into the influence of cognition on eye scanning behaviour, for example, during search tasks or reading (Liversedge & Findlay, 2000). Despite their apparent effortlessness, eye movements can demonstrate a wide array of cognitive processes.

Current Study/ Rationale

Mild traumatic brain injury is a major health issue with a plethora of symptoms. Cognitive impairment is a frequent symptom that significantly affects quality of life. Despite this, there is no universally accepted protocol for assessment of cognitive status in mTBI. Existing methods are vulnerable to a variety of factors that are extraneous to the patient's actual level of function, so there is a need for objective methods to assess the neurobehavioral deficits seen in mTBI patients. Eye-tracking methods have several features that suggest promise as an objective tool for assessing cognitive function in mTBI.

The present scoping review was conducted to survey how eye-tracking tasks have been used in the literature to assess cognitive function in patients with TBI. The primary objective of the review was to determine if eye tracking tasks could be a useful tool in detecting cognitive impairment in patients with mTBI. This objective was addressed by focusing on case-control studies that compared performance on conventional neuropsychological tasks and cognitively demanding eye-movement tasks, to determine if the two kinds of assessments reached similar conclusions about the level of function. The secondary objective of this study was to survey and describe the kinds of cognitively demanding eye movement tasks being used in the mTBI literature.

CHAPTER 2 - METHODS

This scoping review was guided by the Arksey and O'Malley (2005) framework (later revised by Levac et al., 2010). The five stages outlined include: (1) identifying the research question, (2) identify relevant articles, (3) study selection, (4) charting the data and (5) collating, summarizing, and reporting results. Grant and Booth (2009) define a scoping review as "preliminary assessment of potential size and scope of available research literature. Aims to identify nature and extent of research evidence (usually including ongoing research)." Essentially, scoping reviews aim to examine broader concepts where various study designs may be used. Both scoping reviews and systematic reviews use transparent and reproducible methods. However, systematic reviews typically focus on a well-defined question synthesized typically from studies with very structured design (i.e., randomized control trials). A scoping review is advantageous when the literature is heterogenous (Arksey & O'Malley, 2005).

Given the exploratory nature of my research questions, a scoping review was undertaken. The research question was narrowly focused to address a specific question related to the comparison between different ways of assessing cognitive function, which might suggest that a systematic review would be appropriate. However, preliminary examination into the topic showed that this is a new area and has not been extensively studied. Consequently, few studies sought to address this exact research question, and there is tremendous variability in method and measures, making a systematic review impossible. So, a scoping review was conducted to address the research question with the use of various method designs and objectives. An optional sixth stage of the Arksey and

O'Malley (2015) framework involving stake-holder consultation was not undertaken in this review.

Step 1: Identify the Research Question

According to Levac et al., (2010), stage one of a scoping review involves a broad research question but clearly articulated scope of inquiry, health outcomes, and target population. The target population for this scoping review were individuals with mild traumatic brain injury. The CDC definition of brain injury was adopted for this review; "a bump, blow, or jolt to the head or a penetrating head injury that disrupts the normal function of the brain" (Langlois et al., 2006). The health outcome of interest was cognitive status. Thus, the question guiding this review was "can eye-tracking technology be used to effectively detect cognitive impairment in patients with mild traumatic brain injury?".

Step 2: Identify relevant studies

A systematic search of six electronic databases was initially conducted in November 2020 and subsequently updated in October 2021. The following databases were searched for relevant articles published between 1990-2021: PsychINFO, Medline at OVID, CINAHL, Academic Search Premier, Embase, and PubMed Central. These databases were chosen as they encompass peer-reviewed research in the fields of neurology, ophthalmology, neuropsychology, and cognition.

The search strategy was constructed around three main concepts: brain injury, cognitive assessments, and eye-tracking technology. For each concept, both a key term search and a subject heading search was conducted. These searches were combined with the Boolean operator "OR" to ensure an exhaustive search for each concept. These searches were then combined with the Boolean operator "AND" to identity articles that included all three concepts. A list of the key terms/medical subject headings used in the search strategy can be found in appendix A. This process was repeated for all six databases.

Step 3: Study selection

After the electronic database search, the articles were filtered in a three-step screening process: title and abstract screening, full text screening, and extraction. This was accomplished using the citation streamlining software, Covidence. Articles that corresponded to all the exclusion criteria, outlined in Table 1, were included in the review. Collectively, the search yielded 1838 references; once duplicates were removed 1504 references remained to screen. One hundred and forty four of these 1504 references were found from re-running the searches to include the most recent literature (October 2020- October 2021). After the primary exclusion criteria were applied, 186 references were assessed for full text review. Nineteen articles were included in the final review. The PRISMA diagram (Figure 1) demonstrates each stage of the article selection process with the specific exclusion criteria.

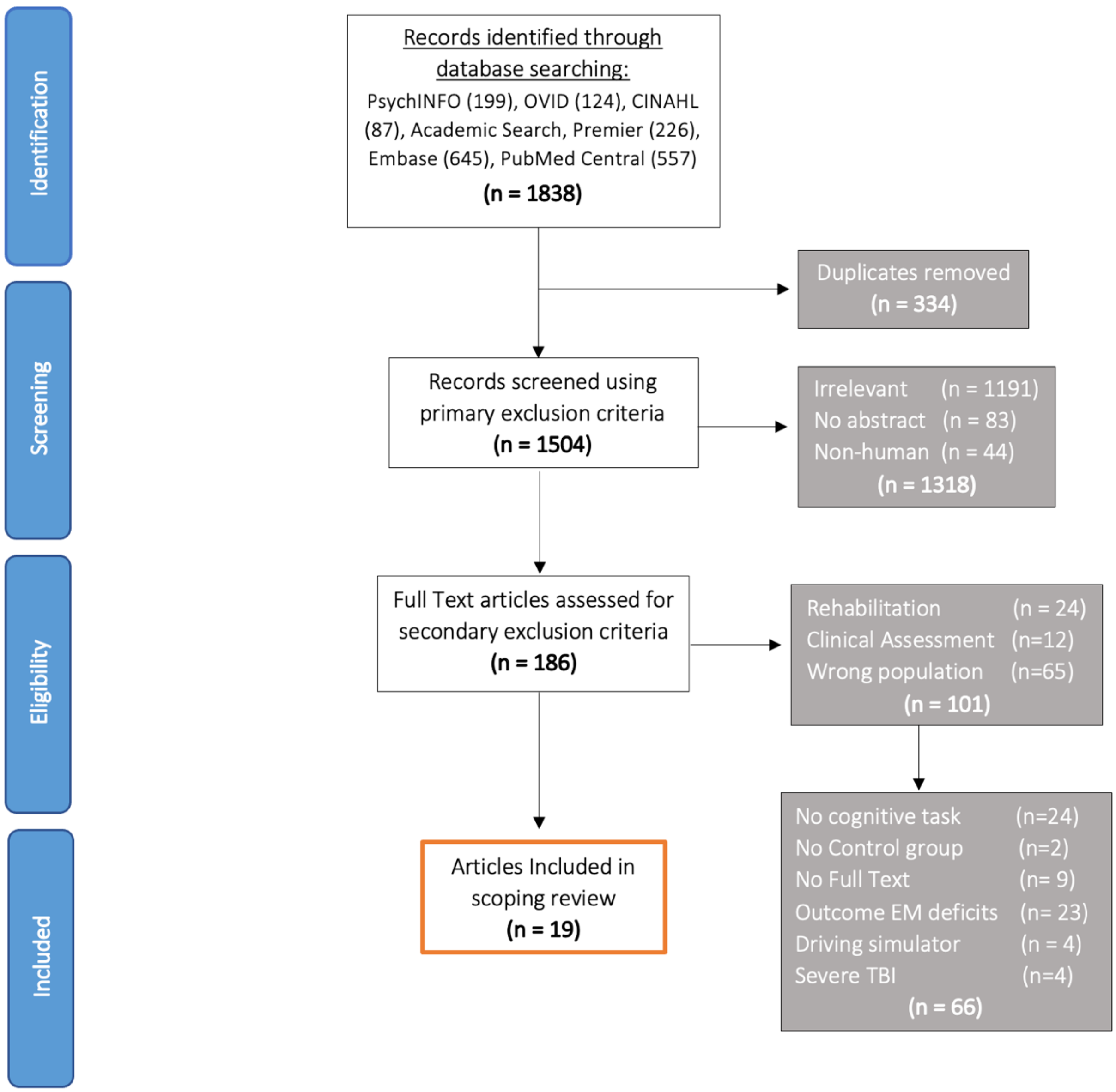
Table 1

Exclusion Criteria for Each Selection Phase

Phase	**Exclusion Criteria**
Title and Abstract Screening	• Missing one or more of the three following concepts: · Eye tracking · Cognitive assessment · Neuro atypical population • No abstract • Animal research
Full Text Review – Primary	• Eye tracking technology used for rehabilitation purposes (not detection/diagnosis) • Clinical assessment of eye movements by clinician, rather than eye tracking technology • Population that was not TBI
Full Text Review – Secondary	• No neuropsychological task included for comparison to eye tracking task • No control group included • No full text included • Eye tracking system was used to assess eye movement deficits not cognitive status • Eye tracking system was incorporated into driving simulator • Population was severe or moderate TBI

Figure 1

Preferred reporting items for systematic reviews (PRISMA) diagram depicting the stages of article selection, exclusion criteria and number of articles removed from each stage



Note. EM = eye movements.

Step 4: Charting the data

A data-extraction form was developed to chart relevant data from the 19 selected articles. Data of interest that was extracted included: title, author, year of publication, location the study took place, number of participants, participant demographic information, inclusion/exclusion criteria, how TBI was defined, cognitive task used, eye tracking task used, cognitive task measured, purpose, outcomes, conclusions, and limitations.

The case-control Newcastle-Ottawa assessment scale was used to assess the methodological quality of the articles and risk of bias. This scale assesses three main criteria: selection, comparability, and exposure with several subcategories. A star-rating system is used to assign a somewhat quantitative assessment of study quality. The lowest possible score is zero and maximum score is nine.

Step 5: Collating, summarizing, and reporting the results

Once the data were extracted and organized, it was synthesized and interpreted for common themes and relationships address the research question. Table 2 provides an overview of the neuropsychological tasks used, eye tracking tasks used and main findings from each in the 19 included articles.

Table 2

Summary of Neuropsychological and Eye Movement Tasks used and their Outcomes in Included Studies

Author	Neuropsychological Battery/Tasks	Eye Movement Tasks	Main Finding
Astafiev et al. 2015	ANT, CVLT-II, COWAT, WMS-III: Spatial span	Circular SP Circular SP with gaps Circular SP with distractor	NP: did not reliably differentiate control subjects from chronic mTBI patients at individual subject level EM: did not reliably differentiate control subjects from chronic mTBI patients, non-significant trend for increased variability of tracking errors in the mTBI group
Barry & Ettenhofer 2016	CPT – manual responses	CPT – saccadic responses	NP: manual omissions more sensitive to invalid responding than saccadic omissions EM: saccadic commission more sensitive to invalid responding than manual commissions Both: TBI simulators group had significantly greater reaction time variability
Clough et al. 2018	HSCT, PASAT, SCWT, SDMT, WAIS III: Digit span	Anti-saccade Pro saccade Switch	NP: no significant differences between Australian rules footballers and control group on any measures EM: Australian rules footballers demonstrated significantly more anti-saccade errors than control group on switch task
Diwaker et al. 2015	ANT, COWAT, CVLT, Finger tapping, SDMT, WAIS III: Spatial span	Circular SP alone Circular SP with gaps Circular SP with distractor	NP: no differences between chronic mTBI group on any subcategory of attention (ANT) but overall reaction time was slower in mTBI. mTBI group was impaired relative to controls on COWAT, CVLT EM: no group differences for continuous tracking condition, but for gap condition, patients lagged behind the target after it's reappearance and were slow to resynchronize their gaze in comparison to controls

Ettenhofer & Barry 2016	CPT – manual metrics Conners CPT II, CVLT-II, D-KEFS, TMT, GP, WAIS IV: Digit span forward and backward, Symbol search)	CPT – saccadic metrics	NP: did not differ by group, number of injuries, or symptom severity EM: mTBI more than 3 times more likely to be impaired on saccadic metrics. Increased number of TBIs, and higher scores on symptom inventory were also significantly associated with higher rates of saccadic impairment
Ettenhofer et al. 2018	n-back CPT TMT (A+B), HVLT-R, WAIS IV: Digit span, Symbol search, Coding	n-back CPT – saccadic metrics	NP: no significance differences between control group and TBI groups on any conventional neuropsychological measures or manual metrics EM: chronic TBI groups demonstrated substantial saccadic impairment, proportional to cognitive demand. Cognitive load did not significantly impact saccadic performance in controls
Ettenhofer et al. 2020	n-back CPT – manual metrics TMT (A+B), WAIS IV - Digit span forward and backward, Digit span sequencing, Symbol search	n-back CPT - saccadic metrics	NP: groups did not differ on any conventional neuropsychological measure. Working memory score on CPT was good predictors of mTBI EM: reaction time variability and inhibition errors were successful predictors of mTBI
Heitger et al. 2009	BADS: Zoo Map test, D-KEFS: Verbal fluency, Color-word interference, RAVL, RCFT, TMT (A+B), WAIS III- Digit span, Similarities, Picture completion, Digit symbol, WMS II: Logical memory	Anti-saccades Reflexive Saccades Memory guided saccades Self-paced saccades Sine and random SP	NP: poorer performance on neuropsychological tasks on initial group comparisons between mTBI and controls. Later controlled for significantly higher IQ in control group. After controlling for this, no significant group differences remained. EM: increased error rate on anti-saccades and memory-guided sequences, less self-paced saccades related to longer inter-saccadic intervals in mTBI group (these effects remained after controlling for IQ)

Hershaw et al. 2017	CPT – manual metrics Conners CPT -II, CVLT-II, D-KEFS: Colour word interference, GP, TMT, WAIS IV: Digit span forward and backwards, Symbol search total score	CPT – saccadic metrics	NP: no age-related performance differences were demonstrated between mTBI and control group on conventional neuropsychological measures or manual metrics EM: more advanced age was associated with longer saccadic reaction times and more no-go inhibition errors in mTBI group compared to controls
Kraus et al. 2007	BVMT, Conner's CPT -II, COWAT, CVLT, GP, PAWAT, SCWT, TMT, TOL, RFFT, WAIS-III: Digit Span and Spatial span,	Anti-saccade (gap and overlap) Gap saccade	NP: did not show significant differences between mTBI and controls (did find differences for moderate and severe) EM: mTBI group committed significantly more errors on anti-saccade than controls
Kraus et al. 2010	BVMT-R, Connors CPT-II, COWAT, CVLT-II, GP, PASAT, RFFT, SCWT, TOL, TMT, WAIS-III: Digit span and Spatial span,	Gap saccade Predictive saccade	NP: mTBI was more impaired than controls on executive function tasks but not memory or attention. EM: gap effect confirmed in all groups through longer latencies in the overlap condition compared to gap condition – magnitude of effect proportional to injury severity.
Maruta et al. 2016	ANT, CLVT	Circular smooth pursuit	NP: mTBI had global reaction time increase but no impairment on subcomponents of attention. Also recalled fewer words on the long-delay recall task, but no differences in the total discriminability score. EM: no difference in performance for visual tracking task
Maruta et al. 2018	ANAM4: SRT	Circular smooth pursuit	NP: performance on SRT was degraded post-concussion EM: the only degradation in visual tracking performance in concussion was horizontal gain

Phillipou et al. 2013	BRIEF, ImPACT	Anti-saccade Prosaccade Self-paced saccade	NP: mTBI had impairment on multiple memory tasks and significantly slower processing speed EM: mTBI made fewer errors on anti-saccade at first time point only
Rao et al. 2021	ImPACT	Anti-saccade Circular SP with gaps Prosaccade	Oculomotor tasks were highly predictive of ImPACT scores and optic nerve sheath diameter.
Suh et al. 2006a	CVLT	Circular SP	NP: lower scores related to attention, working memory, learning, and executive control EM: mTBI group had decreased target prediction (increased phase lag) compared to the control group during the first five cycles of each block
Suh et al. 2006b	CVLT	Circular SP with gaps	NP: mTBI group scored significantly lower than controls on measures related to memory, learning and executive attention EM: mTBI group showed earlier generation of saccades, phase lag, increased eye position error and increased intra-individual variability compared to controls during gap periods.
Ting et al. 2016	SCWT, TMT, MoCA-Phonemic fluency score	Anti-saccade (gap) Prosaccade	NP: mTBI scored worse compared to controls on the Stroop color-word test EM: mTBI had greater latency and error duration during the anti-saccade task than the control group
Williamson et al. 2021	ImPACT	Circular smooth pursuit with gaps	There was greater precision on smooth tracking task among subjects with higher cognitive ImPACT scores. Oculomotor performance was a good predictor of cognitive impairment.

Abbreviations

ANAM4	Automated Neuropsychological Assessment Metrics
ANT	Attention Network Test
BADS	Behavioural Assessment of the Dysexecutive Syndrome
BRIEF	Behavior Rating Inventory of Executive Function
BVMT-R	Brief Visuospatial Memory Test Revised
COWAT	Controlled Oral Word Association Test
CPT	Continuous Performance Test
CVLT	California Verbal Learning Test
D-KEFS	Delis-Kaplan Executive Function System
EM	Eye Movements
GP	Grooved Pegboard
HSCT	Hayling Sentence Completion Test
HVLT-R	Hopkins Verbal Learning Test Revised
ImPACT	Immediate Post-Concussion and Cognitive Testing
MoCA	Montreal Cognitive Assessment
NP	Neuropsychological
PASAT	Paced Auditory Serial Attention Test
RAVL	Rey Auditory Verbal Learning
RCFT	Rey Complex Figure Test
RFFT	Ruff Figural Fluency Test
SCWT	Stroop Color and Word Test
SDMT	Symbol Digit Modalities Test
SP	Smooth Pursuit
SRT	Simple Reaction Time
TMT	Trail Making Test
TOL	Tower of London
WAIS	Weschler Adult Intelligence Scale
WMS	Weschler Memory Scale

CHAPTER 3 - RESULTS

Descriptive characteristics of the included studies

Table 3 provides an overview of the salient characteristics of the included studies. As shown in the table, there has been a significant increase in research in this area in recent years. Years of publication are demonstrated in Figure 2. The average number of participants per study was 63, ranging from 30-158. There was vast variability of amount of time passed since injury and assessment, ranging from within a week to 21 years. Sport-related injuries were included in all studies that reported etiology. Frequency of each etiology within the study populations can be found in Figure 3.

Table 3

Overview of Characteristics of Included Studies

	Number of studies
Location	
USA	15
Canada	1
New Zealand	1
Australia	2
Cohort Age	
Adult	14
Pediatric	1
Mixed	4
Etiology of injury	
Mixed	15
Sports-related	4
Eye Tracking Technology	
D6 desktop tracker	2
EyeLink	9
Grass Instruments model	2
Ober Saccadometer	1
GP3 HD	1
Skalar IRIS infrared	1
SensoMotoric Instruments	1
Bethesda Eye & Attention Measure Prototype	2

Figure 2

Years of Publication of the Included Articles

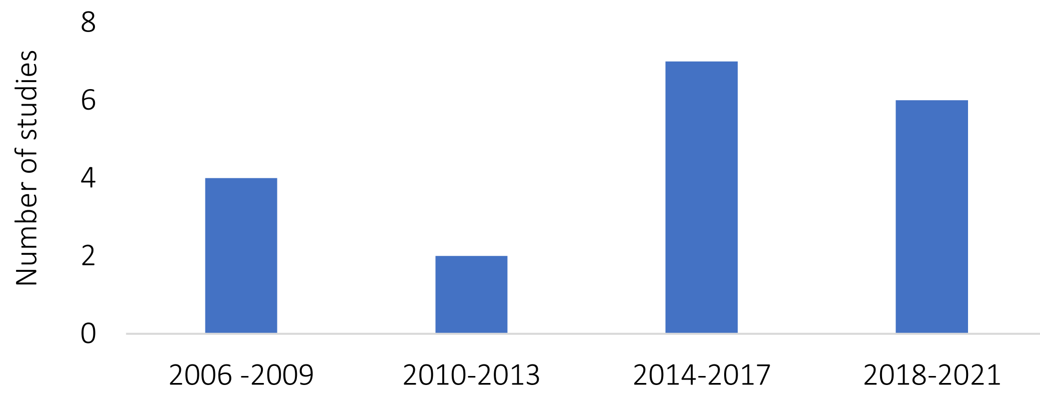
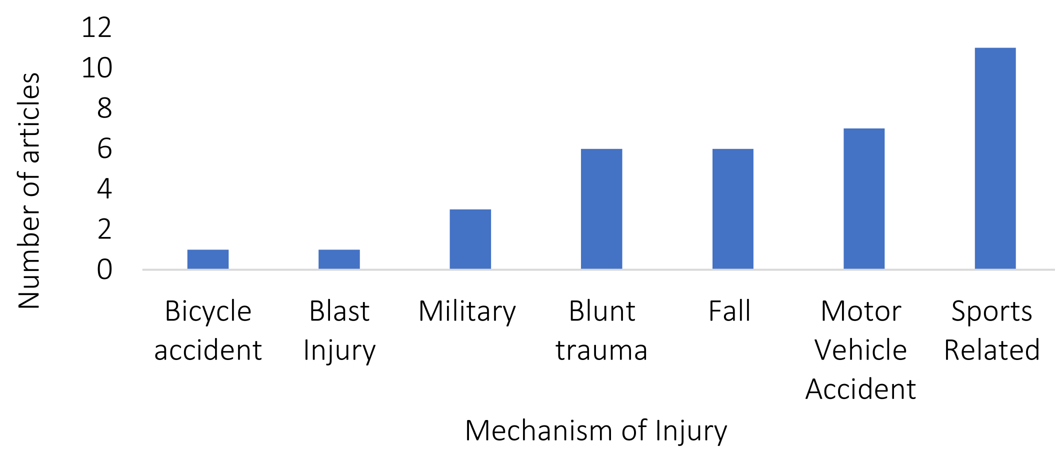


Figure 3

Frequency of Mechanism of Injury in Included Studies



Note: 'Frequency' denotes the number of times each mechanism was included in all the articles.

The table also shows that the predominant eye tracking technology used in the studies was EyeLink devices. Most models were desktop mounted, only two included mobile (head-mounted) units. Two studies used EOG; the remaining studies used video-based units. Two of the video-based units used infrared illumination, while the remaining used visible light.

All studies included in this review were evaluated using the Newcastle-Ottawa Scale for case-control studies. Total scores for each study were converted to Agency for Healthcare and Research and Quality standards of good, fair, and low quality. Conversion thresholds for Newcastle Ottawa scores to Agency for Health and Research Quality standards are outlined in Table 4. Eleven of the 19 articles were deemed good quality.

Table 4

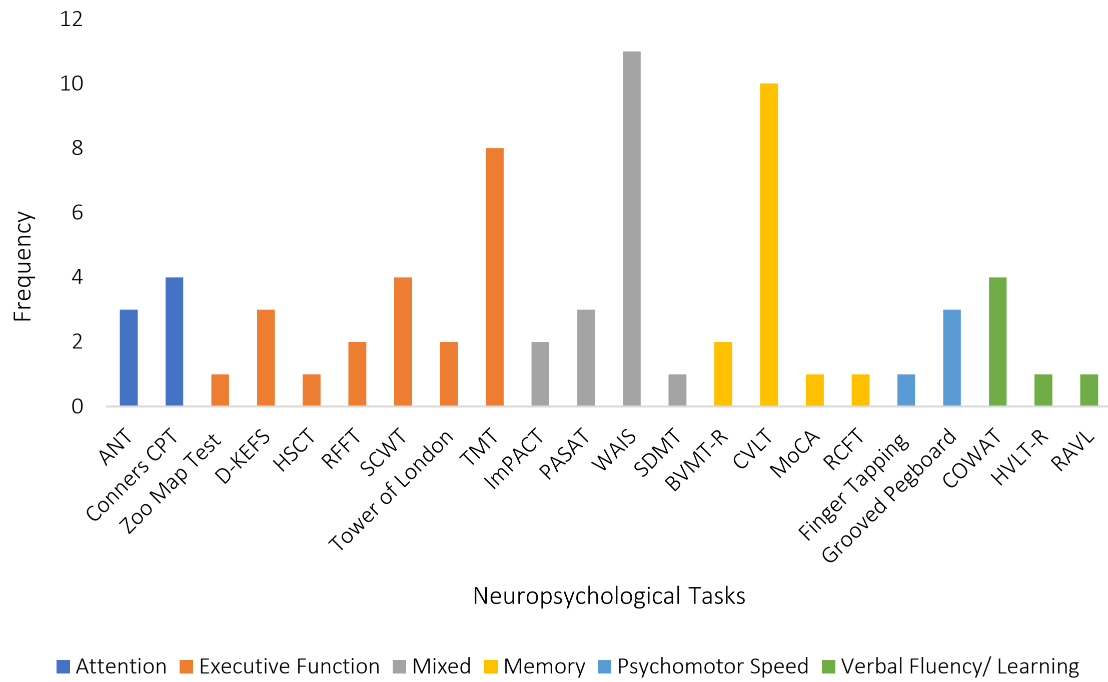
Conversion thresholds for Newcastle Ottawa Scores to Agency for Healthcare and Research and Quality standards

	Good	**Fair**	**Poor**
Selection	3 or 4	1 or 2	2 or 3
Comparability	2	1 or 2	2 or 3
Exposure	0 or 1	0	0 or 1

A wide array of neuropsychological tasks were used, across various domains of cognition. There was an emphasis on executive functions tasks considering the common involvement of the frontal lobes in brain injury. See Figure 4 for a list of neuropsychological tasks used and frequency of administration. For a detailed description of each neuropsychological task see Appendix C.

Figure 4

Neuropsychological Tasks used and Frequency of Administration



Note. ANT = Attention Network Test, CPT = Continuous Performance Task, D-KEFS = Delis-Kaplan Executive Function System, Hayling Sentence Completion Test, HSCT = Hayling Sentence Completion Test, RFFT = Ruff Figural Fluency Test, SCWT = Stroop Colour and Word Test, TMT = Trail Making Test, IMPACT = Immediate Post-Concussion Assessment and Cognitive Testing, PASAT = Paced Auditory Serial Addition Test, WAIS = Weschler Adult Intelligence Scale, SDMT = Symbol Digit Modalities Test, BVSM-R = Brief Visual Spatial Memory Revised, CVLT = California Verbal Learning Test, MoCA = Montreal Cognitive Assessment, RCFT = Rey Complex Figure Test, COWAT = Controlled Oral Word Association Test, HVLT-R= Hopkins Verbal Learning Test, RAVL = Rey Auditory Verbal Learning.

Neuropsychological Tasks vs. Eye Movement Tasks

The primary objective of this review was to determine whether eye tracking tasks are a useful tool in detecting cognitive impairment in patients with mTBI. Each article had a sample of individuals with mild traumatic brain injury complete both a neuropsychological task and an eye movement task to assess cognitive status. Most of the studies did not necessarily set out to test the same research question. This case control design with the two types of tasks, was chosen to be able to extract the relevant data to address the research question. Of the 19 total studies, 17 allowed for comparison of cognitive impairment on the two types of tasks through between group analyses of the mTBI and control group. There were two articles that used between-groups correlations and consequently did not allow for direct comparison of the two methods for presence or absence of group differences.

Of the 17 eligible studies, 9 reported significant differences between patients with mTBI and controls on neuropsychological tasks. Of those nine studies, 7 reported significant group differences on the cognitively demanding eye tracking tasks. Given that neuropsychological tests are the accepted norm for assessing cognitive status in mTBI, this analysis shows that eye-tracking methods generally (7/9 times) lead to the same conclusion of impairment as reached by traditional methods; in other words, the two kinds of tests are usually in agreement about impairment. This suggests a level of concurrent validity for eye-tracking tests as a tool for assessing cognitive function.

Of the 17 eligible studies, 8 reported no significant differences between groups on neuropsychological tests. Intriguingly, however, of those 8 studies, 7 reported significant group differences on the eye tracking tasks. One interpretation of this finding is that eye-tracking tasks are more sensitive to cognitive impairments than neuropsychological tasks, since impairments were revealed using eye-tracking methods that were not detected on neuropsychological tests. There are other possibilities, of course, including that the two kinds of tests are simply measuring different functions. However, the high degree of agreement between assessment methods described earlier (when neuropsychological tests reveal deficits, 7/9 times the eye-movement test agrees) argues against this interpretation.

Therefore, eye movement tasks may detect impairments among patients with mild TBI who are unimpaired on neuropsychological tasks. For a breakdown of the efficiency of eye movement and neuropsychological tasks for determining group differences in cognition, see Table 5.

Table 5

Presence or Absence of Cognitive Impairment on Neuropsychological Tasks and Eye Tracking Tasks in mTBI group

	Year	mTBI Impairment on Neuropsychological Task	mTBI Impairment on Eye tracking task
Barry & Ettenhofer	2016	Yes	Yes
Diwaker et al.	2015	Yes	Yes
Kraus et al.	2010	Yes	Yes
Maruta et al.	2018	Yes	Yes
Suh et al.	2006a	Yes	Yes
Suh et al.	2006b	Yes	Yes
Ting et al.	2016	Yes	Yes
Maruta et al.	2016	Yes	No
Phillipou et al.	2013	Yes	No
Clough et al.	2018	No	Yes
Ettenhofer & Barry	2016	No	Yes
Ettenhofer et al.	2018	No	Yes
Ettenhofer et al.	2020	No	Yes
Heitger et al.	2009	No	Yes
Hershaw et al.	2017	No	Yes
Kraus et al.	2007	No	Yes
Astafiev et al.	2015	No	No

There were 17 articles included in the previous analysis as two of the included articles did not test for statistical differences between cases and controls, but instead used a correlational design to determine the degree of association between different kinds of tests. Both studies administered ImPACT (immediate post-concussion assessment and cognitive testing) to athletes and found a decline over the course of the season.

Oculomotor tasks such as smooth pursuit with gap, visually guided saccade, and anti-saccade task were highly predictive of ImPACT scores.

Types of Eye Movement Tasks

The secondary objective of this review was to survey the types of eye movement tasks that are being utilized to examine cognitive status in mTBI patients. The three categories of eye movement tasks found were: smooth pursuit, saccadic, and dual tasks. See Table 6 for a breakdown of studies within each category.

Table 6

Articles Organized by Category of Eye Movement Tasks Used

	Year	Saccadic Task	Smooth Pursuit Task	Dual Task
Astafiev et al.	2015		*	
Barry & Ettenhofer	2016			*
Clough et al.	2018	*		
Diwaker et al.	2015		*	
Ettenhofer & Barry	2016			*
Ettenhofer et al.	2018			*
Ettenhofer et al.	2020			*
Heitger et al.	2009	*		
Hershaw et al.	2017			*
Kraus et al.	2007	*		
Kraus et al.	2010	*		
Maruta et al.	2016		*	
Maruta et al.	2018		*	
Phillipou et al.	2013	*		
Rao et al.	2021	*		
Suh et al.	2006		*	
Suh et al.	2006		*	
Ting et al.	2016	*		
Williamson et al.	2021		*	

Saccadic Eye Movement Tasks (N= 7)

The simplest of saccadic tasks was the prosaccade task (participant saccades towards a peripheral target). The majority of studies used the anti-saccade task, where the participant is asked to saccade in the opposite direction of the peripheral target. This task engages inhibitory control mechanisms as it requires the participant to inhibit a reflexive saccade to the peripheral target. Some variations of this task included the gap anti saccade where on some trials the central fixation point was extinguished before the peripheral stimulus was presented (gap trial) and other trials the target appeared with the central fixation target still present (overlap). These latter trials, require the participant to disengage attention from the central target to initiate a saccade to the peripheral target. This gap paradigm was used for prosaccade tasks as well. Other types of tasks included switch tasks (anti-saccade and pro saccade), memory guided saccades (performing a memorized sequence of saccades), self-paced saccades (perform as many saccades as possible between two stationary targets in a specified time frame), and predictive saccade (saccade towards a target presented sequentially between two fixed locations). The types of saccadic eye movement tasks are listed by article in Table 7.

Table 7

Types of Saccadic Eye Movement Tasks used in Each Article

	Eye Movement Tasks Used
Clough et al. 2018	Anti-saccade Prosaccade Switch task (Prosaccade and anti-saccade)
Heitger et al. 2009	Anti-saccade Prosaccade Memory guided saccade Self-paced saccade
Kraus et al. 2007	Anti-saccades Gap saccade
Kraus et al. 2010	Gap saccade Predictive saccade
Phillipou et al. 2013	Anti-saccade Prosaccade Self-paced saccade
Rao et al. 2021	Anti-saccade Prosaccade
Ting et al. 2016	Gap anti-saccade Prosaccade

There were no significant group differences found on the simple prosaccade tasks (Clough et al., 2018; Heitger et al., 2009; Phillipou et al., 2013; Ting et al., 2016). However, tasks that incorporated gap conditions noted some interesting differences. Longer saccade latencies were found in the overlap condition than the gap condition, a phenomenon called the gap effect. The overlap condition requires the subject to disengage visual attention from a central fixation point, prolonging saccade initiation. This effect was most pronounced in the moderate TBI group, followed by the mTBI group and finally the control group (Kraus et al., 2010). The anti-saccade task consistently found impairments in the TBI groups. Participants in the mTBI group demonstrated higher error rates and higher switch cost – difficulty switching from a prosaccade trial to the anti-saccade trial (Clough et al., 2018). Additionally, some studies found specific eye movement deficits in the TBI group such as larger absolute position errors of the final eye position in anti-saccades and the gain of the final eye position were hypermetric compared to controls (Heitger et al., 2009; Kraus et al., 2007; Ting et al., 2016). The findings for self-paced saccades were mixed. Some studies found no significant differences between groups (Phillipou et al., 2013), but others found less self-paced saccades and longer intersaccadic intervals in the TBI group (Heitger et al., 2009). Only one study included memory guided saccades but found that higher error rate and marginal impairments with regard to poorer timing and rhythm keeping (Heitger et al., 2009). A predictive saccade paradigm was only used in one study and found that showed that controls showed a more rapid and greater decrease in response latency than the TBI groups. This deficit was proportional to injury severity. In other words, the control group was able to anticipate and catch on quicker than the TBI group (Kraus et al., 2010).

Smooth Pursuit Tasks (N=7)

The same task was used in the seven articles investigating smooth pursuit. The task was to track a stimulus in a predictive circular trajectory. Some studies had a variation of this tasks where the stimulus was continuously visible, or the stimulus disappeared at random intervals (gap condition) before reappearing. The participants were asked to continue to track the trajectory in the absence of the stimulus, predicting the targets movement. Another variation of this task included a distractor stimulus moving in the opposite direction of the target stimulus. Participants were asked to ignore the distractor stimulus and track the target stimulus. Types of smooth pursuit tasks are listed by article in Table 8.

Table 8

Types of Smooth Pursuit Eye Movement Tasks used in each article

	Eye Movement Task Used
Astafiev et al. 2015	Circular pursuit alone Circular pursuit with gaps* Circular pursuit with distractor
Diwaker et al. 2015	Circular smooth pursuit alone Circular smooth pursuit with gaps Circular smooth pursuit with distractor*
Maruta et al. 2016	Circular smooth pursuit alone
Maruta et al. 2018	Circular smooth pursuit alone
Suh et al. 2006	Circular smooth pursuit alone
Suh et al. 2006	Circular smooth pursuit with gaps
Williamson et al. 2021	Circular smooth pursuit with gaps

Note: Task was administered but data not reported

The tasks with tracking of predictive circular trajectory alone were not effective at identifying differences between mTBI participants and controls. Mean eye position error, variability of position error (radial/tangential), mean phase error, and saccade frequency were similar between the groups (Astafiev et al., 2015; Diwakar et al., 2015; Maruta et al., 2016; Suh et al., 2006a). However, if these tasks included gap conditions, there were significant differences between the groups. Participants with mTBI participants demonstrated phase lag, meaning they lagged behind the target after it's reappearance and were slow to resynchronize their gaze. Conversely, the control subjects demonstrated more precise tracking and, in some cases, slight phase lead, tracking ahead of the target. Therefore, the control group was able to anticipate the target speed and continuous change in position. This mTBI group also had larger average radius than controls and higher error variability (Diwaker et al., 2015; Suh et al., 2006b).

Dual Tasks (N=5)

Unlike the two preceding categories of eye movement tasks, in which participants responded solely with eye movements in cognitively demanding tasks, studies in this group included eye movement responses in addition to other forms of responding in a traditional cognitive task. These studies had participants complete a continuous performance task (CPT) with different cue conditions. These conditions included nondirectional cues (provide temporal information on the appearance of target), directional cues (pointing towards to the target), misdirectional cues (pointing away from the target), un-cued (central fixation cross persists through the appearance of the target), gap cues (a blank image replacing the fixation cross), and no-go cues (provide a signal that the participant should not respond to that target). The participant was asked to both press a keyboard key and fixate a target as quickly as possible once it appears. Having both these responses allows for comparison of manual and saccadic metrics. Some studies added another level of difficulty by increasing cognitive load. Low cognitive load trials required a key press and fixation on the target. Moderate cognitive load required the participant to press the key that corresponds to the colour of the target. High cognitive load trials required the participant to press a button labelled ‘same’ or ‘different’, depending on whether the target circle was the same colour or different colour relative to the previous target. The type of CPT paradigm used in the articles is outlined in Table 9.

Table 9

Variations of Continuous Performance Task Used in each article

	Type of Paradigm Used
Barry & Ettenhofer 2016	Basic
Ettenhofer & Barry 2016	Basic
Ettenhofer et al. 2018	Cognitive load
Ettenhofer et al. 2020	Cognitive load
Hershaw et al. 2017	Basic

Every study in this category found saccadic indices on a continuous performance task to be an added benefit in neurocognitive assessment. When comparing rates of impairment on the two types of metrics: saccadic vs. manual, the saccadic metrics often demonstrated more impairments. For example, impairment on individual saccadic metrics was, on average, more than three times more likely to be seen in participants with mTBI than in those in the control group. Compare this to less than one times more likely for manual metrics. Furthermore, rates of saccadic impairment were significantly associated with multiple mTBIs and higher symptomology, this finding did not extend to manual metrics. When incorporating cognitive load into the continuous performance task, there was a significant interaction between groups and load but only for saccadic metrics. The TBI group demonstrated substantial saccadic slowing proportional to cognitive load (most impairment in high load condition). Increased reaction time variability and inhibition errors served as successful predictors of mTBI. In contrast, cognitive load did not significantly impact saccadic performance among uninjured controls. For manual responses, participants across all groups demonstrated increased reaction time as cognitive load demands increased but both groups were affected equally. Eye movement tracking was also useful in identifying invalid responding. Saccadic commissions were more sensitive to invalid responding than manual commissions, and manual omissions were more sensitive than saccadic omissions. Therefore, incorporating saccadic indices could help identify invalid responding and avoid false positives. Additionally, saccadic measures were found to be beneficial in identifying the effect of TBI on cognitive aging. Age was found to be more strongly related to saccadic measures of visual attention in mTBI group than controls. This was demonstrated through slower saccadic response times and more difficulty inhibiting saccadic responses. No age-related performance differences were demonstrated between the mTBI and the control group on manual measures. Overall, saccadic indices yielded greater sensitivity than manual indices to detect cognitive impairment under conditions of increased cognitive demand (Ettenhofer et al., 2018; Ettenhofer et al., 2020), cognitive aging (Hershaw et al., 2017) and invalid responding (Barry & Ettenhofer, 2016).

CHAPTER 4 - DISCUSSION

The primary objective of this review was to assess the utility of eye tracking tasks for detecting cognitive impairment in patients with traumatic brain injury. The majority of studies found that eye movement tasks were effective at detecting cognitive impairments in a mTBI population. In the 9 studies that reported significant impairment on neuropsychological tests, 7 of them additionally reported significant impairment on eye tracking tasks, indicating a high level of agreement. In 8 studies, impairment was not reported on neuropsychological tests, yet in 7 of these studies significant impairments were reported on eye tracking measures which suggests that these tests might be more sensitive to deficits. The secondary objective of this study was to survey and describe the kinds of cognitively demanding eye movement tasks being used in the mTBI literature. Three categories of tasks emerged: saccadic, smooth pursuit and dual tasks involving both saccadic and manual responses.

As noted at the outset, traditional neuropsychological tests of cognitive function after head injury are limited by premorbid intelligence, fatigue, motivation, and reliance on self-report (Millis & Volinsky, 2001; Rees, 2003). The overarching context for this project is to develop improved methods to assess cognitive function following mTBI that eliminate some or all of these limitations. This review set out to ascertain whether there is any evidence that supports the use of eye tracking for this purpose, as a kind of 'proof of concept' exercise. The current study found considerable evidence that eye movement tasks were an effective method to detect whether a cognitive impairment is present.

Development of eye movement-based assessment battery

This evidence lays the foundation to grow this field of research. Certain steps are required to develop this concept into a comprehensive eye-movement based assessment battery. Firstly, future research is required to validate this approach for its use as a detection method for specific cognitive deficits. Comparison studies examining eye movement tasks and neuropsychological tasks within the same cognitive domain would be useful. For example, if the cognitive domain of interest is inhibitory control, an anti-saccade task and a traditional Stroop color-word task would be appropriate tests to administer. If interested in memory, a memory guided saccadic task and California Verbal Learning Test could be used, and so on. This study showed that there is general agreement between the neuropsychological tasks and eye movement tasks for detecting cognitive impairment. However, it would be important to validate whether there is agreement on the two methods within each cognitive domain.

The objectivity of eye tracking makes it a valuable assessment tool. Future studies that support the idea that eye tracking tests are less vulnerable to invalid responding/ malingering than conventional neuropsychological methods are essential. There is some existing research validating this notion through performance validity studies. Barry & Ettenhofer (2016) were able to accurately identify true TBI patients from healthy adults instructed to feign deficits on a continuous performance task using saccadic and manual response metrics. Saccadic commission errors were more sensitive to invalid responding than manual commission errors and there was increased reaction variability in the TBI simulators. Kanser et al., 2020 explored this concept but used eye tracking as an adjunct to assess visual behaviors during traditional neuropsychological tasks. During forced-choice trials, TBI simulators more transitions, fixations, and time spent looking at correct and incorrect response options. These eye tracking indices led to high accuracy in determining group status.

An objective method does not only evade purposely invalid responding, but also functions independent of confounding intrinsic factors (i.e., premorbid intelligence). Heitger et al., (2009) found poorer performance on neuropsychological tasks on their initial group comparisons between TBI participants and controls. However, the control group has significantly higher IQ and depression levels than the TBI group. After controlling for this unexpected selection bias, no significant group differences on neuropsychological measures remained. Whereas oculomotor measures were unaffected by group disparities in depression and estimated intellectual ability. Ettenhofer et al., (2020) also found that estimated intelligence, depression, and PTSD were related to conventional neuropsychological measures and multiple manual metrics on a continuous performance task but was not related to any saccadic metrics. Therefore, oculomotor measures may offer a more objective measure of neurocognitive assessment as it is more resistant to confounding extraneous factors. This study paralleled these findings as eye tracking tasks were often able to detect impairment when conventional methods were not. Perhaps, integrating eye tracking into the regular cognitive assessment could flag more patients that previously would not have received care.

It is important to confirm the validity of this method. Validity refers to whether an instrument is measuring what it is designed to measure. The eye movement tasks in this study were used to detect cognitive impairment. One may ask if the poorer performance in the brain injury group on eye movement tasks is due to a true cognitive impairment or due to eye movement deficits from their injury? Eye movement dysfunction is certainly a symptom after a traumatic brain injury so it important to determine whether these may be influencing the results. This study found that the more basic or rudimentary tasks such as prosaccade task and a simple smooth pursuit task did not yield any group differences. In other words, the TBI group and the control group did not differ on eye movement indices. The more cognitively taxing tasks such as the anti-saccade task, gap saccade, memory guided saccades, predictive saccades and smooth pursuit tracking with gaps did yield group differences. If it were true that eye movement deficits were driving the poor performance in the TBI group, the poor performance should be demonstrated on all eye movement tasks. This explanation does not explain why, for example, there were group differences on the anti-saccade task and not the prosaccade task. These two tasks employ the same type of eye movement, and therefore the same neuroanatomy but do not yield the same results. This confirms that cognition load must be driving this disparity, as it is the only differing factor. However, these are collated findings from multiple studies.

Future research interested in this area could perform simple baseline eye movement tests in a case control to design to rule out the influence of underlying eye movement deficits. Alternatively, TBI group eye movements could be compared to accepted normal values for latency, velocity, and gain. Johnson et al., (2015) paralleled the current study's findings where they had a TBI group and control group compete seven oculomotor tasks. The three tasks that reached significance on group comparisons were the anti-saccade task, self-paced saccades, and memory guided saccades. While reflexive saccade, fixation, sinusoidal, and circular pursuit tasks did not. Once again, specifically the tasks with higher cognitive demand demonstrated differences. Notably, the TBI group exhibited increased fMRI activation during these tasks suggesting reduced processing efficiency and more effort required based on complexity.

Key measurement properties of assessment tools

Any assessment tool benefits from key measurement features such as sensitivity, objectivity, and accessibility. Using methods with high sensitivity is extremely important to ensure impairments are not missed. Timely and sensitive detection of impairments ensures proper recovery time and management. As previously mentioned, high sensitivity can ensure that a second brain injury does not occur before the initial injury has healed. Thus, mitigating potentially fatal scenarios such as secondary impact syndrome.

Advancement in technology has allowed portable, light weight, and cost-effective eye trackers to be widely available. With this rise in mobile eye tracking devices, eye tracking can be implemented in a variety of settings such as sideline or bedside. Research is ongoing to validate the use of smart phones/tablets for eye tracking via the front camera. Valliappan et al., (2020) replicated oculomotor findings on prosaccade, smooth pursuit and visual search tasks compared to expensive desktop eye trackers in a healthy population. Moreover, they were able to achieve comparable accuracy with their method compared to state-of-the-art eye trackers. This shows promise for implementing this method in a TBI population. Considering the lack of hardware involved, this method could easily be administered for sideline evaluation of possible sports related brain injury. Other applications include by the bedside for patients who are poor candidates for chinrest/fore rest configurations due to postural restrictions. This could apply to the elderly population whose frailty does not support this constricted positioning. Or alternately, TBI patients with other co-morbidities that prevent mobility such as using Cspine precautions or orthopedic injuries. Mobile brain injury assessment methods are emerging with focus on eye movement deficit detection, vestibular performance, and neurocognitive tests (Baruch et al., 2016; Quang et al., 2018). The neurocognitive tasks still require a motor response from the participant such as an arm movement or button press. Assessing cognition through eye movement tasks allows for hands free assessment. These methods are then accessible to a wider population of patients such as locked in syndrome patients who have limited to no motor function.

Despite this expansion of accessibility, one group of individuals that would not benefit from this method is those with limitations of eye movements. Causes include cranial nerve palsies and restrictive strabismus stemming from skull fractures. Deficits in ocular motility would likely limit the utility of eye tracking tasks as the individuals may not be able to fixate a target if it is in the field of action of the affected extraocular muscle. For example, an individual with an abducens cranial nerve palsy would have difficulty making a conjugate eye movement to a target in the far periphery without moving their head. Another barrier for these individuals is that they would likely be diplopic thus complicating which target to fixate. However, this study suggests that using eye movement tasks could be useful for detection of *mild* traumatic brain injury. Cranial nerve palsies are much more prevalent in moderate and severe brain injury compared to mild. Jin et al., (2010) examined individuals with TBI and found that 314 had a cranial nerve palsy (I-XII), 80 of those involved cranial nerves III-VI. Only two of the 80 were mild traumatic brain injury. Therefore, this method will exclude some individuals from its use but the prevalence of this group within this population is low.

Systematic approach to scoping review

Articles were limited to case-control design that compared performance on neuropsychological tasks and cognitively demanding eye-movement tasks. This allowed for a direct comparison of whether the two kinds of assessments reached similar conclusions. Direct focused questions such as the one driving this review, are typically a trait of a systematic review. However, this is a fairly new area of research and there were very limited studies that directly addressed this question. Due to this lack of homogenous literature, a systematic review was not possible. Therefore, a scoping review was required to address the question with flexibility of using articles with varying methodology and reasons for conducting the study. This allowed for extraction of relevant information from diverse research studies.

Limitations

This review served primarily as a 'proof of concept' exercise. The exclusion criteria were curated to allow for a comparison of the two assessment methods in a case-control design. This led to the finding that eye tracking is useful for detection of cognitive impairment, but further steps, as outlined previously, are necessary to validate its use as a comprehensive assessment tool. As mentioned above, both a neuropsychological and eye movement task was required for inclusion; due to this the secondary objective of this review may be limited. It is possible that some of the articles excluded used novel eye tracking tasks but did not include a neuropsychological assessment. Thus, the eye tracking tasks used in these articles do not encompass the entirety of the eye movement tasks being used to assess cognitive impairment in the literature. Additionally, patients with ocular motility deficits are not good candidates for this method due to the need for full conjugate eye movements. This population therefore will not benefit from this method, but the proportion of this condition in mTBI is low. This review only focused on static metrics such as reaction time and did not include articles describing the more qualitative gaze behavior. Valuable information about cognitive processes can be draw from factors such as dwell time and areas of interest. However, these indices were not the focus of this review, so these types of articles were not included.

Conclusions

In conclusion, the findings of this review indicate that cognitively challenging eye tracking tasks could be a useful method for detecting cognitive impairment in mTBI population. This method could aid in more sensitive detection, reduce invalid responding and increase accessibility to various populations. The world of eye movement tasks to assess cognitive impairment is evolving and this study lends support for future research to pursue this research area.

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APPENDIX A - Key Terms and Medical Subject Headings used in PsychINFO

	Cognitive Task	Eye Tracking Systems	Brain Injury
PsychINFO			
Key Terms	Cognitive control OR executive function OR cogniti* OR inhibitory control	(visual* OR eye* OR gaze) N3 (track* OR movement*)	"brain injur* OR concuss* OR tbi*
Subject Headings (Thesaurus of Psychological Index Terms)	DE Cognitive Assessment	DE "Visual Tracking"	DE "Brain Injuries" OR DE "Traumatic Brain Injury" OR DE "Brain Concussion"
Medline at OVID			
Key Terms	Cognitive control OR executive function OR cogniti* OR inhibitory control	((visual* or eye* or gaze) ADJ3 (track* or movement*))	("brain injur*" OR concuss* or tbi*)
Subject Headings (Mapping Term)	Executive Function	Eye Movement Measurements	exp Brain Injuries
CINAHL			
Key Terms	Cognitive control OR executive function OR cogniti* OR inhibitory control	(visual* OR eye* OR gaze) N3 (track* OR movement*)	("brain injur*" OR concuss* or tbi*)
Subject Headings	MH "Executive Function"	MH "Eye Movement Measurements") OR (MH "Saccades/EV") EV = evaluation	MH "International Brain Injury Association"
Academic Search Premier			
Key Terms	Cognitive control OR executive function OR cogniti* OR inhibitory control	(visual* OR eye* OR gaze) N3 (track* OR movement*)	("brain injur*" OR concuss* or tbi*)

Subject Headings (Subject Terms)	MH "Executive Function"	MH "Eye Movement Measurements") OR (MH "Saccades/EV") EV = evaluation	MH "International Brain Injury Association"
Embase			
Key Terms	('cognitive control'/exp OR 'cognitive control' OR (cognitive AND ('control'/exp OR control)) OR 'executive function'/exp OR 'executive function' OR (('executive'/exp OR executive) AND ('function'/exp OR function)) OR cogniti* OR 'inhibitory control'/exp OR 'inhibitory control' OR (inhibitory AND ('control'/exp OR control))) AND [1990-2020]/py	(visual* OR eye* OR gaze) NEAR/3 (track* OR movement*)	'brain injur*' OR concuss* OR tbi*
Subject Headings (Emtree)	'cognitive assessment'/exp OR' cognitive assessment'	'eye tracking'/exp	'brain injury'/exp
PubMed Central			
Key Terms (Includes MeSH Terms)	"Cognitive control" OR "cognitive function" OR executive function OR "inhibitory control"	"eye tracking" OR "eye movement system"	"brain injury" OR concussion OR TBI

*Controlled Vocabulary Terms: PsychINFO = Thesaurus of Psychological Index Terms, Academic Search Premier= Subject Terms, CINAHL = CINAHL Subject Headings, EMBASE= Emtree terms, and Medline at OVID = Medical Subject Heading (MeSH) terms

APPENDIX B - Newcastle Ottawa Quality Appraisal

		Selection				Comparability	Exposure			
Authors	**Year**	**Is the case definition adequate?**	**Representative-ness of the cases**	**Selection of controls**	**Definition of controls**	**Comparability of cases and controls on the basis of the design analysis**	**Ascertainment of exposure**	**Same method of ascertainment for cases and controls**	**Non-response rate**	**Total Score**
Astafiev et al.	2015		*	*	*					**3**
Barry & Ettenhofer	2016	*	*	*	*	**	*	*		**8**
Clough et al.	2018		*	*	*	**	*	*		**7**
Diwaker et al.	2015		*	*		**				**4**
Ettenhofer & Barry	2016	*	*	*	*	**	*	*		**8**
Ettenhofer et al.	2018	*	*	*	*	**	*	*		**8**
Ettenhofer et al.	2020		*	*	*	*	*	*		**6**
Heitger et al.	2009	*	*	*	*	**	*	*		**8**
Hershaw	2017	*	*	*	*	**	*	*		**8**
Kraus et al.	2007		*	*	*	**				**5**
Kraus et al.	2010		*	*	*					**3**
Maruta et al.	2016		*	*	*	**	*	*		**7**
Maruta et al.	2018		*	*	*	**	*	*		**7**
Phillipou et al.	2013		*	*			*			**3**
Rao et al.	2021		*	*	*	**	*	*		**7**
Suh et al.	2006	*			*	**				**4**
Suh et al.	2006				*	**				**3**
Ting et al.	2016	*	*	*			*	*		**5**
Williamson et al.	2021		*	*	*	**	*	*		**7**

APPENDIX C – Description of Neuropsychological Tasks

Assessment	What it Tests	Description of Task
Attention		
Attention Network Test	Alerting network Orienting network Executive network	Indicate the direction of the arrow – may appear individually or in an array of 5. Array may be congruent (>>>>>), incongruent (<<><<) or neutral (--->---). The target arrow(s) is/are preceded by different types of cues: central, double, no cue or spatial cue.
Conner's Continuous Performance Task	Sustained and selective attention	Push the spacebar when any letter, except "X", appears
Executive Function		
Delis-Kaplan Executive Function System	Mental flexibility, inhibition, problem solving, planning, impulse control, abstract thinking	Comprises of 9 tests: Trail making, verbal fluency, design fluency, color-word interference, sorting, twenty questions, word context, tower test, proverb test.
Hayling Sentence Completion Test	Response initiation and suppression	Two sets of 15 sentences each having the last word missing. In the first section the examiner reads each sentence aloud and the participant must complete the sentences. The second part requires participants to complete a sentence with a nonsense ending word (and suppress a sensible one)
Ruff Figural Fluency Test	Nonverbal capacity for initiation, planning, and divergent reasoning	Draw as many figures as possible utilizing five different dot configurations
Stroop Colour and Word Test	Response inhibition	Participants are presented with a series of colour names presented in different font colours. They are asked to name the colour of the font and not read the word. (*Ex: BLUE – respond "RED"*)
Tower of London	Planning, problem solving	Rearrange beads or disks to match a model in a minimum number of moves
Trail Making Test	Mental flexibility, visual attention	Part A: the circles are numbered 1 – 25, participant should draw lines to connect the numbers in ascending order Part B: the circles include both numbers (1 – 13) and letters (A – L); as in Part A, the patient draws lines to connect the circles in an ascending pattern, but with the added task of alternating between the numbers and letters *(ex:1-A-2-B-3-C, etc.)*

Zoo Map Test (Subtest of Battery - Behavioural Assessment of Dysexecutive Syndrome)	Planning, problem solving	Plan a route to visit 6 of possible 12 locations in a zoo. Firstly, in a demanding, open-ended situation where little external structure is provided, and secondly in a situation that involves simply following a concrete, externally imposed strategy.
Mixed		
Immediate Post-Concussion Assessment and Cognitive Testing	Verbal memory, reaction time, visual-motor speed, and visual-memory	Includes six modules: verbal memory, visual memory, visual motor, reaction time, impulse control, subjective symptoms
Paced Auditory Serial Addition Test	Attention, vigilance, and short-term memory	Add each number to the one immediately preceding it. *(Ex: if presented 1, 7, 5, 4, add the first two numbers (1 + 7) and respond with the number 8. Then add the second two numbers (7 + 5) and respond with the number 12. Then add the third two numbers (5 + 4) and responds with the number 9.)*
Symbol Digit Modalities Test	Processing speed, visual attention	Substitution task where the participant is given a reference key to replace geometric figures with numbers.
Weschler Adult Intelligence Scale	Intellectual ability	*Verbal IQ*: Verbal comprehension index- vocabulary, similarities, information, comprehension; Working memory index- arithmetic, digit span, letter number sequencing *Performance IQ*: Perceptual organization index – picture completion, block design, matrix reasoning; Processing speed- digit symbol, coding, symbol search
Memory		
Brief Visual Spatial Memory Revised	Working memory capacity	A grid of boxes appears on the screen and begin flashing in a sequence. The participant is asked to click the boxes in the same sequence. If correct, the next sequence will be one box longer. Performance is indicated by the average number of boxes remembered during the task
California Verbal Learning Test	Episodic verbal learning and memory	The experimenter reads a list of 16 nouns aloud, the participant is asked to recall as many words as they can in any order (i.e., free recall). An interference list (list B) is presented that shares two categories from List A (e.g., fruit and tools) and has two unshared categories (e.g., fish and kitchen utensils). The CVLT ends with a recognition task, where the experimenter presents the subject with a

		44-word list, and the subject must indicate whether it is a target word or a distractor.
Montreal Cognitive Assessment	Executive function, short-term memory, attention, language ability, visuospatial abilities	A 30-point test, time of administration is typically 10-12 minutes. Score of 26 or greater is considered normal
Rey Complex Figure Test	Visuospatial abilities, memory, attention, working memory	Reproduce a complicated line drawing, first by copying it freehand (recognition), and then drawing from memory (recall)
Psychomotor Speed		
Finger Tapping	Motor control in upper extremities	Keep tapping an index finger on a table until the examiner instructs the patient to stop. A modification of this requires the patient to perform a repetitive movement with the opposite hand, such as supination and pronation, while having them finger tap with the other hand
Grooved Pegboard	Dexterity, fine motor	Place the pins in the holes as quickly as possible, with the score being the number of pins placed in 30 seconds. Usually done with dominant and non-dominant hand
Verbal Fluency		
Controlled Oral Word Association Test	Verbal fluency	Produce as many words as they can that begin with the given letter (F, A, or S) within a 1-min period. Subjects are also instructed to exclude proper nouns, numbers, and the same word with a different suffix
Hopkins Verbal Learning Test	Verbal learning and memory	Listen carefully and attempt to memorize the words that examiner reads off – followed by free recall of participant. Participant is read 24 words and is asked to say "yes" after each word that appeared on the recall list (12 targets) and "no" after each word that did not (12 distractors). Half distractors are drawn from same semantic categories as the targets and half are unrelated
Rey Auditory Verbal Learning	Verbal memory	Five presentations of a 15-word list are given, each followed by attempted recall. This is followed by a second 15-word interference list (list B), followed by recall of list A.