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A Bayesian meta-analysis on the effects of mTBI on attention in an adult population

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Résumé

Contexte. Les traumatismes craniocérébraux légers (TCCl) constituent un problème important en raison de leur coût humain et financier exorbitant. Au cours des trois premiers mois post accident, les patients souffrent généralement de symptômes somatiques, affectifs et cognitifs. Parmi ces derniers, les difficultés d'attention sont souvent rapportées. Si certaines publications mettent en évidence de tels déficits, d'autres ne vont pas dans ce sens. Par conséquent, l'objectif principal de ce projet est d'aborder les résultats contradictoires de la littérature en déterminant si le fonctionnement attentionnel des adultes, dans les trois premiers mois à la suite du TCCl, est réellement affecté et si oui, déterminer quel processus attentionnel est le plus touché. **Méthode.** Une revue systématique a identifié 13 études répondant aux critères de sélection. Le premier ensemble de données était composé de sept études ayant rapporté des mesures d'attention sélective et le second contenait les cinq autres études rapportant un score composite d'attention. Une méta-analyse bayésienne robuste a été réalisée. **Résultats.** Des preuves extrêmes en faveur d'un effet sur l'attention sélective ont été trouvées, ainsi que des preuves faibles pour soutenir l'absence d'hétérogénéité et la présence d'un biais de publication. La taille moyenne de l'effet et les intervalles de crédibilité sont *d* = .369, *IC* 95% [.208, .522]. Pour le score d'attention composite, des preuves faibles ont été trouvées pour l'effet, l'hétérogénéité et le biais de publication. La taille moyenne de l'effet et les intervalles de crédibilité sont *d* = .248, *IC* 95% [.039, .485]. **Conclusions.** Nos résultats offrent des preuves claires de déficits d'attention sélective dans une population d'adultes ayant subi un TCCl dans les trois mois suivant leur blessure. Quant à l'utilisation d'un score composite de l'attention, les données sont inconcluantes. Des recommandations sont émises pour les futures recherches dans le domaine.

Mots-clés : Traumatisme craniocérébral léger, attention, neuropsychologie clinique, statistique Bayésienne, méta-analyse

Abstract

Context. Mild traumatic brain injuries (mTBI) are a serious issue given their exorbitant human and financial cost. Within the first three months, patients often report somatic, affective, and cognitive symptoms. Of the latter, attentional difficulties are often reported. While some literature points to evidence for such deficits, others disagree. With the many varying methods in assessing attention present in the literature, many clinicians remain unsure of the best course of action when faced with limited tools and time. Therefore, the goal of this project is to determine if attentional functioning is altered in adults within the first three months following mTBI, and if so, to document which attentional processes are more likely to be impacted. A second is to provide better data for clinicians and recommendations for future studies in this field. **Method.** A systematic review identified 13 studies that met the selection criteria. The first data set was comprised of seven studies that reported selective attention measures and the second contained the remaining five studies reporting a composite score of attention. A robust Bayesian meta-analysis was conducted. **Results.** Evidence in favor of an effect on selective attention was found, along with weak evidence to support the absence of heterogeneity and the presence of publication bias. The posterior mean effect size and credible intervals came to *d* = .369, 95% *CI* [.208, .522]. As for the composite score of attention, weak evidence was found for the effect, the heterogeneity, and the publication bias favor of an effect for the composite score was found. The posterior mean effect size and credible intervals came to *d* = .248, 95% *CI* [.039, .485]. **Conclusions.** Findings support for the hypothesis of a selective attention deficits in an adult mTBI population within three months of their injury. The evidence based on a composite score of attention is inconclusive. Recommendations for future research methodology are also offered.

Keywords: traumatic brain injury, attention, clinical neuropsychology, Bayesian statistics, meta-analysis

Table of Content

List of tables

List of Figures

List of Acronyms

BF	Bayes factor
BMA	Bayesian model-averaged
CI	Credible interval
CPT	Continuous performance test
D-S	Digit-Symbol substitution
DLPFC	Dorsolateral prefrontal cortex
GCS	Glasgow Coma Score
mTBI	Mild traumatic brain injury
PASAT	Paced Auditory Serial Addition Test
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RoBMA	Robust Bayesian meta-analysis
SAAM	Sleep/fatigue Attention Anxiety Memory
SD	Standard deviation
SE	Standard Error
TBI	Traumatic brain injury
TCCl	Traumatismes craniocérébraux légers
TEA TS	Test of Everyday Attention Telephone Search subtest
TMT	Trail Making Test
USA	United States of America

“*The Brain—is wider than the Sky—*

For—put them side by side—

The one the other will contain

With ease—and you—beside—"

Emily Dickinson, 1862

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1. Introduction

Mild traumatic brain injuries (mTBI) are associated with exorbitant human and financial cost (Bélanger et al., 2005). Following a mTBI, patients often report symptoms in three main clusters: somatic (physical and/or sensory), affective (post traumatic stress disorder, anxiety and/or depression), and cognitive (Bélanger et al., 2005; Borgaro et al., 2003; Cassidy et al., 2004; Dikmen et al., 2017; Hiploylee et al., 2017; Iverson, 2006; Prince & Bruhns, 2017). While studies differ in terms of the most reported somatic symptoms, headaches, sleep disturbances, and fatigue are most recurrent (Hiploylee et al., 2017; Ponsford et al., 2000; Prince & Bruhns, 2017). Concurrently, common cognitive symptoms include issues in attention, memory, processing speed, and multitasking (Hiploylee et al., 2017; Prince & Bruhns, 2017; Truchon et al., 2018). While many symptoms seem to lessen after three months, studies found that some patients continue to report a variety of somatic, affective, and cognitive difficulties months or years after the injury, with the latter type of symptoms interfering the most with daily life (Hiploylee et al., 2017; Truchon et al., 2018; Williams et al., 2010).

Of the cognitive sequalae that are reported within the first three months of an injury, some authors contend that impairments in attention, which are involved in activities of daily life, academic performance, social and professional activities, are impacted (Erez et al., 2009; Mazaux et al., 1997), while others do not (Bélanger & Vanderploeg, 2005; Ponsford & Kinsella, 1992). This contradiction can be due to multiple factors, not the least of which being that the existing literature that incorporates attentional measures seldom follows an established methodology to measure the effect of mTBI on attention. Patients can be tested at various times since their injury, ranging from immediately to months to years. Mild TBI groups are sometimes composed of patients with a variety of causes for their mTBI, from vehicular accidents, to blast injuries to athletic injuries. Different studies will use differing ways to assess attentional constructs. While some guidelines have been created, such as the Institut National d'Excellence en Santé et en Service Sociaux (INESSS) and the American Congress of Rehabilitation Medicine (ACRM) task force, such documents are based on research that has limitations of its own. Therefore, many clinicians are left with limited directions to follow. It has been mentioned that the lack of a universally accepted definition of mTBI, heterogenous study methodology and issues within the attention literature make it difficult to navigate this body of research (Cassidy et al., 2004). These can potentially be the causes of such disparity between studies that find an impact on attention and others who do not. Therefore, the goal of this project is to document deficits in attentional functioning in community dwelling adults, within the first three months of their mTBI, using a rigorous meta-analysis methodology. Additionally, recommendations will be made to guide future research in the field.

2. Theoretical Context

2.1 Mild traumatic brain injury

2.1.1 Prevalence

In 2014, roughly 155,000 people have experienced a traumatic brain injury (TBI) in Canada (Canada, 2018). In Quebec, approximately 12,000 individuals suffer from a TBI per year with vehicular accidents accounting for 45% of injuries and falls being 30% (Info-TCC, 2007). The main victims of TBI are men aged between 15 to 24 years of age (Info-TCC, 2007). A national study reported that the estimated cost for the treatment and rehabilitation of TBI is expected to reach 8.2$ billion in 2031 (Ghajar, 2000). Being the leading cause of death and disability of individuals under the age of 40 (Canada, 2018), the development of efficient methods of prognosis, assessment, treatment, and rehabilitation strategies is crucial. It has been reported that an underestimation of the rates of mTBI exists in the literature (Ryu et al., 2009). This can be due to poor documentation of key diagnostic information, inconsistent diagnostic procedures and failing to account for the fact that many patients who suffer a mTBI do not always go to hospitals, and instead visit their family practitioners (Ryu et al., 2009). In Ontario, it has been reported that the incidence rates of hospital-treated mTBI were 493 or 653/100,000 when including family physician cases (Ryu et al., 2009). According to the Centers for Disease Control and Prevention, the leading cause of mTBI in 2014 in the United States of America (USA) were falls, especially in children below 17 years of age and older adults aged 65 years or older (CDC, 2019). The same report revealed the second leading cause, accounting for 17% of hospital emergency visits in 2014, as being struck by or against an object. Vehicular accidents were found to be the leading cause of hospitalizations among adolescents and adults aged 15 to 44 years of age. A recent study of the incidence of mTBI treated in emergency departments in the USA from 2006 to 2012 showed a significant increase from 569.4/100 000 in 2006 to 807.9/100 000 in 2012 (Lefevre-Dognin et al., 2021). Although the per person cost associated with moderate to severe TBI is higher than mTBI, the latter incurs an overall cost that is three folds larger since it constitutes the majority of TBI diagnoses (Theadom et al., 2018).

2.1.2 Diagnosis and pathophysiology

Mild TBI is characterized by a period of an altered state of consciousness, such as confusion or disorientation, as well as a score ranging between 13 and 15 on the Glasgow Coma Scale (GCS) (Ghajar, 2000), a clinical tool used to measure the severity of a TBI (Teasdale & Jennett, 1974). In addition, a loss of consciousness lasting less than 30 minutes and a post-traumatic amnesia lasting less than 24 hours must be observed (Theadom et al., 2018; Truchon et al., 2018). Finally, any other transient neurological sign, convulsion or an intracranial lesion that does not require surgery are usually associated with mTBI as well (Truchon et al., 2018). A small number of patients who present with mTBI show evidence of intracranial abnormalities following a computed tomography scan taken the day of the injury (Waljas et al., 2015a). This subgroup of patients is said to have “complicated mTBI”, which is associated with worse short-term and long-term outcome (Iverson, 2006; Waljas et al., 2015b). In the case of an uncomplicated mTBI, the difficulty in diagnosis stems from the fact that the observed characteristic alternation of consciousness is similar to the physiological effects of an adrenaline rush or intoxication (Katz et al., 2015).

The forces caused by rotational head acceleration and deceleration during a TBI causes widespread tissue deformation in the brain and microstructural pathophysiological changes (Blennow et al., 2012; Prins et al., 2013; Smith, 2016), which are detectable in the acute and chronic phases post-injury (McInnes et al., 2017). The effects of those disturbances can be observed through diffusion tensor imaging, whereby an increase in radial diffusivity results in reduced microstructural integrity of the myelin sheath (Katz et al., 2015). These forces lead to axonal injuries that result in structural and subcellular changes within the axon cylinder (Buki & Povlishock, 2006). Specifically, the cell membrane of the axon, now riddled with pores and defects, alters its permeability, and provides a route for intraaxonal calcium influx, leading to calpain activation (Laskowski et al., 2015). This, in turn, leads to structural alterations to the axonal cytoskeleton, which disrupts both anterograde and retrograde transport, and eventually causes swelling in adjacent axons with axotomy to follow (Buki & Povlishock, 2006; Creed et al., 2011; Shojo & Kibayashi, 2006). In addition, neurofilament compaction occurs and may mediate the disruption of axonal transport (Laskowski et al., 2015). Included in these pathophysiological changes is a neurometabolic cascade, characterized by altered neurotransmitter activity, that causes a hypermetabolism and subsequent decrease in brain excitability (McInnes et al., 2017; Prins et al., 2013). While focal injuries (ex. cortical contusions) usually cause a more severe TBI, diffuse injuries (ex. diffuse axonal injury) are most often seen in mTBI (Blennow et al., 2012). Crucially, the cause of an mTBI can result in a different neuroanatomical profile and different symptomatology (Sharbafshaaer, 2018).

2.1.3 Post-concussive symptoms

Following a mTBI, different somatic symptoms occur, notably headaches, dizziness, and fatigue (Hiploylee et al., 2017; Katz et al., 2015; Ponsford et al., 2000). Both headaches and dizziness seem to persist in a significant minority of patients at 3- and 6-month post-injury (Katz et al., 2015). In addition, certain affective symptoms, such as depression and anxiety are commonly reported within the first three months of the injury (Borgaro et al., 2003; Konrad et al., 2011). This phenomenon may be due to either the neurobiological effects caused by the injury, such as neurochemical changes and fluctuations in cerebral glucose metabolism (Prins et al., 2013) and/or its psychological burden (Katz et al., 2015). Some have posited that alterations to the limbic-frontal network is responsible for the development of depression after a mTBI (McCrory et al., 2009). Others found that many who suffered from persistent symptoms had a psychological risk factor one month after the injury, such as depression, stress and/or low resilience (Losoi et al., 2016). Previous research has also identified various cognitive symptoms that are crucial for social reintegration post-injury (Hallock et al., 2016). In the first three months post-injury, mTBI patients have reported feeling foggy, a lack of concentration, forgetfulness, and losing track of thoughts and/or conversations (Borgaro et al., 2003; Katz et al., 2015). In most cases, many of the cognitive symptoms resolve themselves within the first three months, making this period clinically important as cognitive difficulties are seldom present after this threshold (Hiploylee et al., 2017; Katz et al., 2015).

It has been suggested that pathophysiological changes may manifest as cognitive impairment (McInnes et al., 2017). While previous literature revealed acute impairments in many cognitive domains, including executive functions, learning, memory, language, and processing speed (Bélanger et al., 2005; Borgaro et al., 2003; Foley et al., 2010; Gauthier et al., 2018; McInnes et al., 2017; Smith et al., 2015; Truchon et al., 2018; Williams et al., 2010), this project focuses on attentional deficits given that pathophysiological effects of mTBI can occur in areas deemed important for various attentional processes. For instance, right rostral anterior cingulate volume loss has been observed in patients and was correlated with sustained attention deficits, as measured by the PASAT (Wu et al., 2016). Studies have also reported that attentional control is related to activation in the dorsolateral prefrontal cortex (DLPFC) (Chung et al., 2014). Not surprisingly, using repetitive transcranial magnetic hyperstimulation over the course of four weeks (5 times per week) on mTBI patients over their left DLPFC, researchers observed various results. Notably, a reduction in reported postconcussive symptoms and improvements in multiple cognitive measures including tests used to measure attention (Koski et al., 2014). The researchers conducted a three-month follow-up to assess the duration of the benefits from the intervention and found that such effects were limited, such that booster sessions would be required to maintain the improvements observed (Koski et al., 2014). Some findings also show that the integrity of the myelin sheath in the left anterior corona radiata accounts for specific variation in the executive component of attention in both healthy controls and in mTBI patients (Niogi et al., 2008). Multiple studies have tried to elucidate the impact of mTBI on attention, however, an operational definition of attention is in order given the various types of attentions found in the literature and the many models they are associated with.

2.2. Attention

2.2.1. Defining Attention

Attention, in its simplest form, has been conceptualized as the gateway for information flow in the brain (Cohen et al., 1993). Over the years, many have proposed ways to describe attention in terms of a complex system of interacting processes (Strauss et al., 2006). Based on findings in fields such as cognitive neuropsychology, electrophysiology and neuroimaging, many models of attention were conceptualizedseperating attentional processes into various components (Sohlberg & Mateer, 2001; Strauss et al., 2006). One such model, first proposed by Posner and Peterson described the attention system in the brain as having a discrete anatomical basis that can be divided into three networks: alerting, orienting and executive (Petersen & Posner, 2012; Posner & Peterson, 1990). The first network, *Alerting*, is akin to a sense of alertness. Its cognitive homologue can be thought of as the maintenance of vigilance and performance during a task (Petersen & Posner, 2012). They further suggest that to measure the functionality of this network, one would introduce a warning signal that would act as a cue prior to the target's presentation. This would lead to the replacement of the resting state with a new state that involves the preparation, detection, and response to the target (Posner & Peterson, 1990). The resulting decrease in reaction time to the target after a cue was indicative of the speed of alerting attention (Posner & Peterson, 1990). Some neuroimaging studies found that vigilance tasks that tap into the alerting network rely on the right hemisphere and thalamic areas (Sturm & Willmes, 2001), while others point to the left hemisphere (Fan et al., 2005). The second network, *Orienting*, refers to the ability to prioritize sensory input by selecting a modality or location

(Petersen & Posner, 2012). Recent neuroimaging studies point to the frontal eye fields and the interparietal sulcus as active areas when the presentation of an arrow cue was focused on (Corbetta & Shulman, 2002). Finally, the *Executive* control network refers to a specific awareness that is created when the detection of a target occurs. The shifted awareness creates an interference that causes the detection of another target to become slower (Posner & Peterson, 1990). An elaboration to this framework, proposed in Peterson and Posner (2012), found two independent executive networks. The first, the cingulo-opercular control system, is used as a stable background maintenance for task performance, while the second, the frontoparietal system, relates to task switching (Dosenbach et al., 2008). Despite the popularity of the Posner and Peterson model of attention, other theories of attention have been proposed. Specifically, the need for attentional rehabilitation in patients with brain injury led to the development of the clinical model of attention by Sohlberg and Mateer (2001). Unlike other models, this view relied on experimental attention literature, clinical observation, and subjective complaints by TBI patients to derive five components of attention (Sohlberg & Mateer, 2001). *Focused* attention refers to the ability to respond to specific stimuli, be it visual, auditory, or tactile. *Sustained* attention, the ability to maintain a consistent response during a task, was divided into the subcomponents of vigilance and working memory. The former refers to the ability to focus on a task, while the latter, the ability to manipulate and hold information in mind. *Selective* attention is the ability to ignore distracting stimuli while maintaining a cognitive or behavioral set. *Alternating* attention refers to the concept of flexibility, shifting the focus of attention from one task to another. Finally, *divided* attention is the ability to respond to two or more tasks simultaneously (Sohlberg & Mateer, 2001).

Currently, terms like alertness, arousal, vigilance, focused attention, selective attention, divided attention, sustained attention, concentration are commonly used despite the lack of a consensus on their exact meaning (Strauss et al., 2006). Indeed, while Sohlberg and Mateer (2001) make a distinction between focused and selective attention, others use them interchangeably (Lezak et al., 2012; Stirn, 2018). A similar issue arises with alternating attention, which is considered by some as the executive process of shifting (Diamond, 2013), sometimes referred to as shifting attention (Eccleston, 1995; Miyake et al., 2000) or cognitive flexibility (Lezak et al., 2012; Miyake & Friedman, 2012; Moriarty et al., 2011). Along with the varying terminologies comes another hurdle in this literature in that tests commonly used to assess an attentional construct typically measure more than one attentional process (Stirn, 2018; Strauss et al., 2006). For instance, some studies have used the Paced Auditory Serial Addition Test (PASAT) as a measure of divided attention (Audoin et al., 2003; Christodoulou et al., 2001; Cicerone, 2002; Gronwall & Wrightson, 1974; Sohlberg & Mateer, 2001; Webbe & Ochs, 2003) and others, as a measure of sustained attention (Dyche & Johnson, 1991; Parsons & Courtney, 2014). Similarly, the Trail Making Test (TMT) has been widely used to measure divided attention and cognitive flexibility (Bowden, 2017; Kopp et al., 2015; Lezak et al., 2012; Llinas-Regla et al., 2017), sustained attention (Escalona et al., 2000; Jeffs & Darzins, 2007; Sohlberg & Mateer, 2001), focused attention (Stebbins, 2007), and alternating attention (Sohlberg & Mateer, 2001). In the Lezak's Neuropsychological Assessment (2012) manual, attention measures are sectioned into *Concentration/Focused Attention* tests, in which vigilance is included, *Complex Attention tests*, and *Divided Attention tests*. Furthermore, many tests that measure aspects of attention require other abilities, such as processing speed (Mathias & Wheaton, 2007), rendering interpretation of performance a delicate process. For instance, the n-back task, typically utilized to measure working memory (Au et al., 2015; Cappell et al., 2010; Heinzel et al., 2014; Lezak et al., 2012; Linares et al., 2018), involves many processes such as sustained attention, coordination, updating, switching and others (Bopp & Verhaeghen, 2018).

2.2.2. Current attention research in mTBI

The current state of the attention literature in mTBI contains many varying methodologies and results which leads to contradictory findings on how attentional capacities in such a population are measured and addressed. Some studies point to clear attentional deficits (Bélanger et al., 2005; Konrad et al., 2011; Lutkenhoff et al., 2020; Mathias & Wheaton, 2007; Rowley et al., 2017), while others do not (Bélanger & Vanderploeg, 2005; Ponsford & Kinsella, 1992). Studies can be found reporting on difficulties in attentional functions that range from sustained attention (Beaulieu-Bonneau et al., 2017; Dockree et al., 2006; Pontifex et al., 2012; Sinclair et al., 2013)(), to selective attention (Dymowski et al., 2015; Ettenhofer & Barry, 2016; Ziino & Ponsford, 2006), and to divided attention (Cyr et al., 2009; Robertson & Schmitter-Edgecombe, 2017). The inconsistencies with respect to the impact of mTBI on attention may be caused by varying methodological approaches. The rapidly changing prognosis of mTBI patients compared to their more severe counterparts adds a confounding element to studies who combine TBI severities (De Simoni et al., 2016; Lengenfelder et al., 2002; van Donkelaar et al., 2005). Even when investigating mTBI populations specifically, few studies have been found that looked at attention in this population. In many of them, although attention is not the primary outcome, specified attentional constructs are omitted and general terms, such as “attentional domain” or “attention”, are used (Heitger et al., 2006; Little et al., 2010). This creates an issue for clinicians who are left unsure as to the type of attention that needs investigation, the model of attention being used and how to best approach the rehabilitation process. Furthermore, given that a test can measure multiple types of attentional constructs, a study can be using a specific test to measure one type of attention, while another is using it for a different type of attention. For instance, the Digit-Symbol substitution test (D-S) is used by some researchers to assess sustained attention (Munivenkatappa et al., 2016), by others to assess selective attention (Simpson & Schmitter-Edgecombe, 2000), all the while being a measure of alternating attention according to Sohlberg & Mateer's (2001) model of attention. The literature search also revealed that some studies contain patients who have been tested at various times since their injury in the same group, some within three months and others beyond (Hawley, 2001; Moller et al., 2014; Schnabel & Kydd, 2012). A potential confounding element given that many symptoms are resolved after three months for most patients (Hiploylee et al., 2017). Other studies include, within the same group, patients with various and/or unknown causes, from vehicular accidents, to sports, to military accidents (Catena et al., 2007; Killgore et al., 2016; McIntire et al., 2006; Sosnoff et al., 2008) and repeated TBIs (Catena et al., 2007). As previously discussed, the cause of injury can play a role in the neuroanatomical profile of patients and potentially affect their cognitive performances (Sharbafshaaer, 2018). While the realities of research can make it difficult to control for all these elements or to find participants that fit specific inclusion criteria, the resulting effect is the lack of a clear answer as to how attention is affected in mTBI.

2.3. Objectives

The various methodological approaches to measuring attention in an mTBI population has left a void for many clinicians. Not only is a more standardized view needed, but quantitative evidence is also necessary to accurately assess attentional sequelae following mTBI. Therefore, the initial goal of the current meta-analysis is to investigate the impact of mTBI on all types of attentional functions within three months of the injury in a community dwelling adult population. However, given the limited findings of the literature search detailed below, we will conduct an analysis that is specifically exploring the evidence of the effect of mTBI on selective attention and the viability of a composite score of attention.

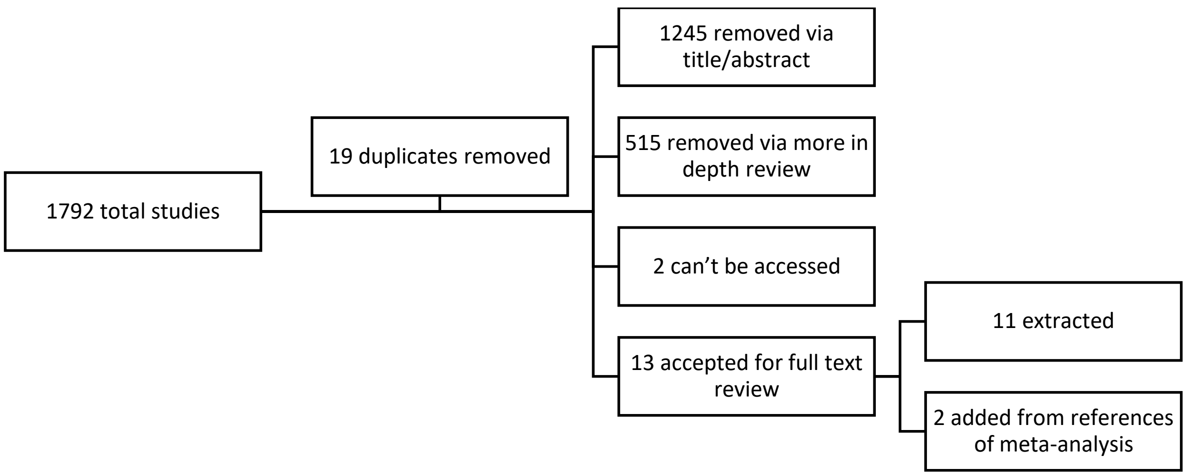
3. Methods

The report of this meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement provided by Moher, Liberati, Tetzlaff, Altman, and The PRISMA Group (Moher et al., 2009).

3.1. Literature Search

Prior to the literature search, which was conducted in August 2020, the inclusion criteria for the meta-analysis were established. To be eligible for inclusion, the articles needed to (a) include a mTBI group and a control group for comparison, (b) have patients injured within the last three months, (c) report at least one attention outcome measure, (d) exclude military personnel, veterans and athletes as participants to avoid blast injuries and multiple TBIs, (e) exclude comorbid ailments or a history of brain injury (i.e. stroke, previous TBI, epilepsy), (f) report the necessary information to calculate an effect size, (g) be published after the year 2000, (h) include adults (18+), and (i) be written in the English or French language. The studies did not have to report effort testing for inclusion in the meta-analysis; however, if the researchers stated that a group demonstrated low effort/motivation to perform well in the tasks, this sample would not be included in analysis. The literature review was conducted through an online search of the PubMed and PsycInfo databases. The electronic search included injury-related (i.e., traumatic brain injur*, concussion*, head injur*, head trauma*), attention-related (Attention*, vigilan*, distract*, concentrate*, Executive function*) and language-related (English and French) search terms. The electronic search yielded 1792 results and a manual search of reference lists from the meta-analysis by Bélanger and colleagues (2005) gathered two additional articles for further review. Ultimately, 13 articles met the inclusion criteria for the meta-analysis.

Figure 1. Literature search breakdown



3.2. Data Extraction

Using a common data collection instrument (www.covidence.org), two reviewers (Ramzi Houdeib and Catherine Gagnon) independently extracted information from each study and judged whether they adhere to the inclusion criteria. Both reviewers extracted TBI characteristics (i.e., operational definition of mTBI, cause of injury, time since injury onset), participant characteristics (i.e., target population, age, sample size, control group, matched variables, potential confounds) and statistical information (i.e., effect sizes, means, standard deviations, tests used for attention). In assessing attentional outcomes, studies in our sample varied in how they classified their measures. Some tasks were attributed to measure one kind of process in one study, and a different one in another. Therefore, to approach this heterogeneity, we decided to follow what the authors of the respective studies claimed their test measured. However, if a study did not specify exactly the type of attention measured and instead used a general label (ex: "Attention", "Attentional function"), then we classified which type of attention this measure belongs to based on the literature and discussion amongst the authors of this meta-analysis. If a study included multiple measures of different attentional constructs, one measure was taken to meet the assumption of independent observations. Of those measures, we prioritized selective attention as it seemed to be the most recurrent form of attention measured among our included sample of studies upon review.

The following are the measures we used from the studies included. Stapert and colleagues (2006) used the time needed to complete condition 3 of an abbreviated version of the Stroop colour word task as a measure of "selective attention" (see also Lezak et al., 2012). Chen and colleagues (2012) used the CPT measures of Omission error, Commission error and Hit Reaction Time as collectively measuring "sustained and selective attention". We opted to use omission errors as an indicator of selective attention, given that they were indicated as such in the CPT normative manual (Conners, 2000; Hall et al., 2016). Shee and colleagues (2012) used the CPT measures of Simple Reaction Time, Vigilance, and Distractibility to assess "Attentional Function". For this meta-analysis, we opted to use the measure of distractibility as it is related to selective attention, as indicated by the normative manual of the CPT (Conners, 2000). Mathias and colleagues (2004) used various tasks from the Test of Everyday Attention (TEA) to assess different forms of attention. They used the accuracy and timing of the Visual Elevator task and the time per target measure of the Telephone Search task to assess "selective attention". Finally, the Telephone Search While Counting subtest was used for "sustained" and "divided attention" (Mathias et al., 2004). Of the different measures reported in Mathias and colleagues (2004), we chose to use the result of the telephone search as a measure of selective attention. We selected it over the Visual Elevator task since the technical manual of the TEA describes it as such. Beaupré and colleagues (2012), another study in the analysis, also used this task as part of a group of tasks described as “Attentional Tasks” and so, here again, we used it as an indicator of selective attention. Dikmen and colleagues (2017) used the TMT A to obtain a measure of “attention” and the TMT B for “inhibitory control”. While both have been associated with selective attention (Stirn, 2018), we kept the TMT A as it was mentioned as the measure of attention in their study. In the study by McAllister and colleagues (2001), participants were given a battery of neuropsychological tests, among which some were allegedly assessing “attention/concentration” and “executive function”. Of the reported results from the study, the CPT measures of Simple Reaction Time (number correct and reaction time), Vigilance (number correct and reaction time), and Distractibility (number correct and reaction time) were considered. Since there is no mention of the attentional construct being assessed, the distractibility accuracy was chosen as the measure of selective attention (based on the CPT normative manual descriptors). Wu and colleagues (2018) used separate measures of the CPT (distractibility and vigilance) to assess “sustained attention”. Although they specify a type of attention, we decided to keep the measure that is associated the most with selective attention, distractibility (Conners, 2000). This was done to keep the same terminology used by the authors of the articles, as well as the technical manual of the CPT. Choosing the selective attention measure was done because we do not have other measures of sustained attention in the other studies. Therefore, given such a low sample size for this type of attention, and to adhere to the assumption of independent observations, the decision to keep the selective attention measure was done. Finally, five studies in our sample used a “composite score of attention” comprised of the TMT A, the Paced Auditory Serial Addition

Test (PASAT), the Stroop and the Digit-Symbol substitution test. Table 1 lists the attention-related measures used in the analysis of this paper along with the attentional constructs to which they were assigned.

Table 1. Attention measures used for each included study

Articles	Tasks (measure)
Selective Attention	
Mathias et al (2004)	TEA TS (time per target)
Stapert et al (2006)	Stroop (completion time of condition 3)
Shee et al (2016)	CPT (Distractibility Accuracy)
Dikmen et al (2017)	TMT A (Time)
Beaupré et al (2012)	TEA TS (time per target)
McAllister et al (2001)	CPT (Distractibility Accuracy)
Chen et al (2012)	CPT (Omission errors)
Wu et al (2018)	CPT (Distractibility reaction time, ms)
Composite Score of Attention	
Articles	**Tasks**
Mayer et al (2012)	
Mayer et al (2009)	
Yeo et al (2011)	TMT A + PASAT + Stroop + D-S
Ling et al (2013)	
Mayer et al (2015)	

Note. TEA TS Test of Everyday Attention Telephone Search subtest; TMT Trail Making Test; D-S Digit-Symbol substitution; PASAT Paced Auditory Serial Addition Test

For each cognitive test, the reviewers extracted the mean and standard deviation for the mTBI and control groups to calculate an effect size for each measure (i.e., *d*; Cohen, 1988). Although a study (Beaupré et al., 2012) reported measures at different time periods of the recovery process, only data within three months of injury were extracted for inclusion in this meta-analysis.

The reviewers also assessed the quality of the studies based on a method used for concussion research (Comper et al., 2010). This procedure ranks studies based on the Oxford Centre for Evidence-based Medicine guidelines (OCEBM) (*Oxford Centre for Evidence-Based*

Medicine 2011 Levels of Evidence, 2011) to categorize them as either Category A or B. The OCEBM procedure contains six criteria to which a study must have three or less violations to be classified as Category A. These criteria range from whether the study has operationally defined mTBI, to whether its control group was matched on more than two variables (education level, age, history of concussion, etc), to whether potentially confounding variables were described by the authors. This process was followed to allow us to identify any studies with methodological issues that could impact their findings. The study quality rankings produced by the two reviewers, as well as the data points for the effect size calculations were compared to ensure interrater reliability. Reviewers were fully consistent in their results with minor discrepancies being discussed and resolved. The effect sizes and extracted variables for the studies included in this meta-analysis are displayed in Table 2.

Table 2. Studies included in this meta analysis

SELECTIVE ATTENTION STUDIES	Group	n	*Mean* Age (*SD*)	%Male	*Mean* Yrs of Education (*SD*)	mTBI definition	TSI	Effort testing	Study Quality	ES (SE)
Mathias et al (2014)	mTBI ctrl	40 40	32.4 (12.7) 32.4 (12.7)	80 80	12.4 (2.3) 12.7 (2.1)	GCS of 13-15, LOC ≤ 20 min	4 weeks	Questionnaire	Level 4, A	0.532 (0.228)
Stapert et al (2006)	mTBI ctrl	99 91	34.7 (16) 36.5 (14.3)	58.6 50.5	4 (2) 4.2 (1.8)	ACRM	< 2 weeks	N/A	Level 4, A	0.519 (0.148)
Shee et al (2016)	mTBI ctrl	91 86	33.7 (13.7) 47.9 (10.2)	61.5 31.4	14.3 (2.6) 15.9 (2.4)	ACRM	~ 1 month	N/A	Level 4, A	0.282 (0.151)
Dikmen et al (2017)	mTBI ctrl	421 120	33.7 (15.2) 31 (13.7)	25 71.7	12.4 (2.5) 12.1 (2.5)	any period of LOC, ≥ 1h PTA, Positive imaging, GCS of 13–15	1 month	Questionnaire	Level 4, A	0.316 (0.104)
Beaupré et al (2012)	mTBI ctrl	15 17	39 (13) 31 (11)	66.7 58.8	13 (3) 14 (2)	ACRM	2.2 ± 0.5 months	N/A	Level 4, A	0.612 (0.362)
McAllister et al (2001)	mTBI ctrl	17 12	31.8 (12.5) 27.8 (8)	44.4 50	15.2 (3.2) 13.7 (1.4)	ACRM	Post PTA	N/A	Level 4, A	0.4 (0.381)
Chen et al (2012)	mTBI ctrl	20 18	36.6 (12.7) 34.9 (10.5)	50 55.6	15 (2.7) 16 (2.1)	ACRM	1 month	N/A	Level 4, A	0.178 (0.326)
Wu et al (2018)	mTBI ctrl	19 23	35 (12) 35.6 (14.1)	57.9 52.2	16 (2) 15 (3)	ACRM	< 1 month	N/A	Level 4, A	0.778 (0.321)
COMPOSITE SCORE STUDIES										
Mayer et al (2012)	mTBI ctrl	22 22	25.5 (4.6) 25.3 (4.5)	40.9 40.9	13.5 (2) 14.3 (2.3)	ACRM	< 21 days	TOMM	Level 4, A	0.526 (0.307)
Mayer et al (2009)	mTBI ctrl	15 15	27.2 (7.6) 27.3 (7.4)	50 50	13.1 (2.5) 14.4 (2.3)	ACRM	< 21 days	TOMM	Level 4, A	0.442 (0.370)
Yeo et al (2011)	mTBI ctrl	30 30	27.3 (9.5) 26.9 (9.2)	43.3 43.3	12.9 (2.4) 13.4 (2.1)	ACRM	1 week	TOMM	Level 4, A	0.337 (0.260)
Ling et al (2013)	mTBI ctrl	50 50	27.9 (9.2) 27.4 (8.9)	51 51	13.1 (2.2) 13.9 (2.1)	ACRM	2 weeks	TOMM	Level 4, A	0.246 (0.201)
Mayer et al (2015)	mTBI ctrl	46 46	28.9 (9.8) 28.4 (9.9)	52.2 52.2	13.2 (2.6) 13.8 (2.3)	ACRM	3 weeks	TOMM	Level 4, A	0.019 (0.209)

ACRM American Congress of Rehabilitation Medicine, Ctrl. Control, ES Effect Size, SE Standard Error, GCS Glasgow Coma Scale, LOC Loss of Consciousness, mTBI Mild Traumatic Brain Injury, PTA Post-Traumatic Amnesia, TSI Time Since Injury, TOMM Test of memory malingering

3.3. Statistical analysis

3.3.1 Effect size & standard error of effect size calculation

To conduct a Bayesian meta-analysis, a Cohen's *d* effect size and the standard error (SE) of effect size were required. For each attention measures extracted from the included studies, the effect size was calculated. When the measure was an accuracy score, the following formula (Eq. 1) was used to calculate the effect size (Cohen, 1988):

(1) $$d = \frac{M_{ctrl} - M_{mTBI}}{SD_{pooled}}$$

Where

(2) $$SD_{pooled} = \sqrt{\frac{(n_{mTBI}-1)s_{mTBI}^2 + (n_{ctrl}-1)s_{ctrl}^2}{n_{mTBI}+n_{ctrl}-2}}$$

Here, s^2 and *n* are the variance and sample size of each group, respectively. However, when the measure in question was a response latency or number of errors, the higher score signifies a worse performance. To account for this, an inverted effect size (-*d*) was used.

To calculate the SE of the effect sizes, the following formula (Eq. 3) was used (Hedge & Olkin, 2014):

(3) $$SE_d = \sqrt{\frac{n_{mTBI}+n_{ctrl}}{n_{mTBI}*n_{ctrl}} + \frac{d^2}{2(n_{mTBI}+n_{ctrl})}}$$

3.3.2. Robust Bayesian meta-analysis

Robust Bayesian meta-analysis (RoBMA) is a model-averaged meta-analytical framework in the presence of publication bias that uses Bayesian model-averaging (Gronau et al., 2017) in combination with selection models (Maier et al., 2021). The first component of RoBMA, Bayesian model-averaged (BMA) meta-analysis, typically yields four models which vary based on whether they assume an overall effect to be present or absent, and whether they assume across-study heterogeneity (random effects) or not (fixed effects). However, in many instances, more than two models are often considered. In this case, the framework considers the change from prior to posterior odds for sets of models defined by including vs. excluding a specific parameter (Gronau et al., 2020; Hinne et al., 2020). The resulting "inclusion Bayes factor" enables BMA to consider all models simultaneously and quantify the evidence for the presence or absence of a meta-analytic effect and across-study heterogeneity. The resulting Bayes factor (BF), a continuous measure of evidence, is labeled into various categories to aid interpretation such that values between 1 and 3 provide "weak" evidence for the alternative hypothesis and values between 0.33 and 1 provide "weak" evidence for the null hypothesis; a BF between 3 (0.33) and 10 (0.1) is interpreted as "moderate" evidence; a BF between 10 (0.1) and 30 (0.03) is interpreted as "strong", and a BF with a value over 100 (below 0.01) is interpreted as "extreme" (Jeffreys, 1961; Wagenmakers et al., 2018). The process of BMA removes the need to base our conclusions on a single model since the overall posterior distribution for the meta-analytic effect is a weighted combination of the estimates of each model in our analysis (Gronau et al., 2020). This is quite desirable when significant posterior uncertainty remains about whether a fixed effect or a random effect model is most suitable. The second component of RoBMA, selection models, allows us to test for and adjust for publication bias given that it is a confound that can lead to an overestimation of effect sizes (Karr et al., 2014; Maier et al., 2021; Rothstein et al., 2005). While multiple statistical methods have been developed to tackle this issue, simulations have shown that most methods perform poorly whenever the individual studies are not exact replications of each other and when the true effect size varies across studies (i.e. heterogeneity) (Carter et al., 2019; McShane et al., 2016). Indeed, selection models have been found to perform well under conditions of high heterogeneity (Maier et al., 2021; McShane et al., 2016).

To apply the Bayesian framework in this meta-analysis, the model parameters of effect size (μ), heterogeneity (τ), and publication bias weight functions (ω) are assigned prior distributions. We selected two different prior distributions to assess the sensitivity of the posterior distribution to different prior beliefs. The first, a default prior distribution ($\mu_{default}$), models how one has no prior knowledge of an effect of mTBI on attention. The default prior distribution for the effect size in RoBMA is a normal distribution with mean 0 and standard deviation of 1 (Maier et al., 2021). The second, a truncated prior distribution, favors the hypothesis that mTBI affects attention measures. In other words, one has knowledge of an effect but not its strength. While this distribution uses the same parameters as $\mu_{default}$, it is truncated at zero to incorporate the directedness of the hypothesized effect. For the between-study heterogeneity parameter τ of both selected effect size priors (default and truncated), Gronau and colleagues (2020) recommend an empirically informed prior distribution approximated by an Inverse-gamma (1, 0.15) based on heterogeneities from psychological meta-analyses (Van Erp et al., 2017). The resulting posterior mean effect sizes are reported with a credible interval (CI), in which the true effect size falls with 95% probability. For the publication bias, the decision was made to test our models against three types of selection processes that may or may not contribute to publication bias. The first does not adjust for a publication bias, therefore assumes no publication bias such that all studies, significant or not, are published. The second selection process is a two-step model that assumes that significant studies are always published, and non-significant studies are published 50% of the time. The third selection process is a three-step model that assumes that significant studies are always published, marginally significant studies are published 66% of the time, and non-significant studies 33% of the time. (Bartoš, Maier & Wagenmakers, 2020).

Our final RoBMA analysis thus focused on models with the default prior distributions for the existence of the effect and models with the truncated prior distribution assuming directionality. All Bayesian analyses were conducted using JASP 0.14.1, JASP Team (Bartoš et al., 2020), on three different data sets. Given that selective attention measures outnumbered the other types of attention, the first data set was comprised of selective attention measures exclusively. The second data set combined all measures that used a composite score for attention to test whether a composite score could be a useful alternative to implement in the clinical setting. Finally, a robustness check was conducted as well (see Appendix 1).

4. Results

4.1. Systematic Review

The 13 eligible studies reported a total of 13 mTBI groups and 13 control groups (11 non-injured healthy controls and two non-head trauma control group) (Beaupré et al., 2012; Chen et al., 2012; Dikmen et al., 2017; Ling et al., 2013; Mathias et al., 2004; Mayer et al., 2015; Mayer et al., 2009; Mayer et al., 2012; McAllister et al., 2001; Shee et al., 2016; Stapert et al., 2006; Wu et al., 2018; Yeo et al., 2011). One study contained a group of complicated mTBI (divided into a GCS of 15 subgroup and GCS of 13-14 subgroup), another of uncomplicated mTBI (GCS of 13-15) and a control group (Dikmen et al., 2017), all of whom were given the TMT A. We combined the performance of all mTBI groups to obtain one mean and one pooled SD that would be compared to the control group's data. For the mean, we found the average of the means of all groups on the task and to calculate the SD, the pooled SD formula (eq. 2) was used but with a 3rd group included. Seven out of 13 studies reported effort testing, with two of them using questionnaires on litigation (Dikmen et al., 2017; Mathias et al., 2004) and five of them using the

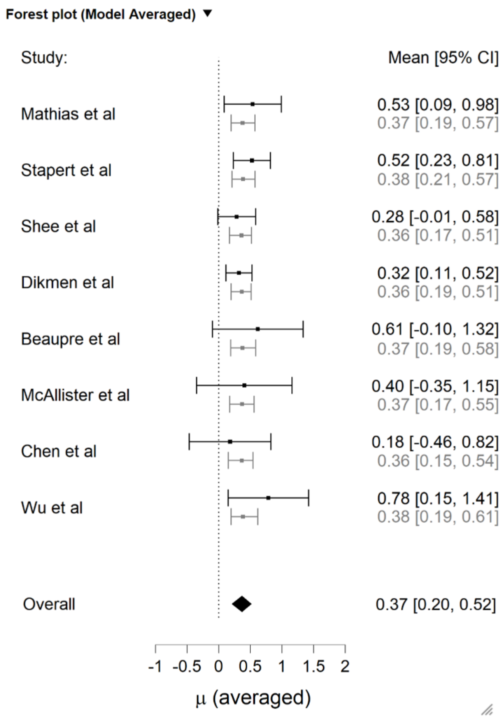
Test of Memory Malingering (Ling et al., 2013; Mayer et al., 2015; Mayer et al., 2009; Mayer et al., 2012; Yeo et al., 2011). Mayer and colleagues (2015) found that the control group had a lower score and an increased variability compared to the mTBI group. Despite these findings, they report that the performance was typically in the normal range for both groups (Mayer et al., 2015). Although the remaining six studies did not consider effort, the research context did not clearly incentivize low effort from the participants. In total, the included studies had 888 participants in the mTBI groups, with a mean age of 31.8 years (SD = 13.9), a mean education level of 13.9 years (SD = 12.9), with 41.7% of participants being males. Most studies included participants with a time since injury of approximately a month or less. One study (Beaupré et al., 2012) tested participants at an average of 2.2 months after their injury (SD = 0.5). The control groups included 572 participants, who had an average age of 31.7 years (SD = 11.7), a mean of 13.3 years of education (SD = 2.3), with 54% of participants being male. While most studies used healthy controls, two studies (Dikmen et al., 2017; Wu et al., 2018) used trauma controls who had injuries unrelated to TBI. It is important to note that some studies contain more participants in their demographic data than for the neuropsychological testing data as some had to be removed from the project. Three studies removed a mTBI patient due to extraneous situations (Ling et al., 2013; Mayer et al., 2009; McAllister et al., 2001). Two of the three concerned studies removed a healthy control as well to maintain an equal sample size among groups (Ling et al., 2013; Mayer et al., 2009). The meta-analytic calculations (effect size, standard errors) conducted in this paper reflect these changes. Following the subcategories specified by Comper et al. (2010), all studies received a OCEBM Level 4 Category A designation by both independent reviewers.

4.2. Meta-analysis

The effect of mTBI on selective attention will first be discussed, followed by the composite score of attention.

When exploring the effect of mTBI on selective attention measures, the posterior distributions revealed that the most likely models contain an effect. Specifically, the fixed effect alternative model based on the default prior distribution took up 24.5% of the posterior probability, while both the fixed and random effect alternative models based on the truncated prior took up 49.2% and 17.3% of the posterior probability respectively. When sets of models were compared, the inclusion BF revealed extreme evidence in support of the presence of an effect (BF_{10} = 504.82) but weak evidence was found to support the absence of heterogeneity (BF_{τ} = 0.355) and the presence of publication bias (BF_{ω} = 1.27). The meta-analytical conditional effect size estimate, that was model averaged over models assuming the existence of effect, was found to be *d* = .369, 95% CI [.208, .522]. Figure 2 shows the forest plot with the calculated effect sizes for each study and their credible intervals in black, along with the estimated effect sizes and their credible intervals in grey.

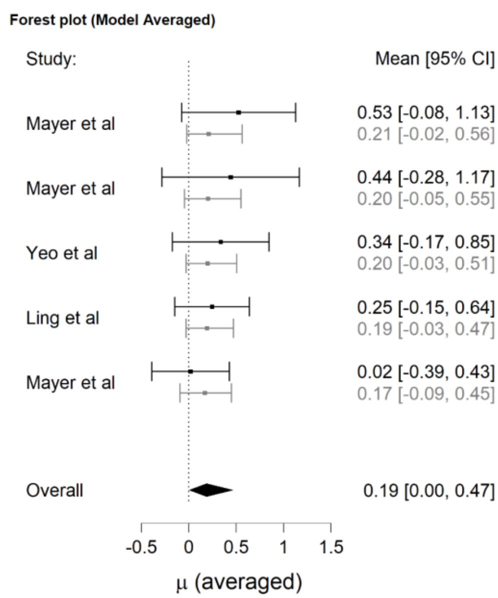
Figure 2. Forest plot of Selective attention measures



Reported mean effect size and 95% credible intervals (black) for each study included in the meta-analysis. Estimated mean effect size and 95% credible intervals (grey) for each study. Overall effect size and 95% credible interval when all studies are combined.

When exploring the use of a composite score of attention for mTBI patients, the posterior distributions revealed weak evidence for an effect. Indeed, when sets of models were compared, the inclusion BF revealed that the data weakly supported the presence of an effect (BF_{10} = 1.51). Furthermore, the results provided a weak support for absence of the heterogeneity (BF_{τ} = 0.533) and not enough evidence for either absence or presence of the publication bias (BF_{ω} = 0.455). The meta-analytical conditional effect size estimate, that was model averaged over models assuming the existence of effect, was found to be *d* = .248, 95% CI [.039, .485]. Figure 3 shows the forest plot with the calculated effect sizes for each study and their credible intervals in black, along with the estimated effect sizes and their credible intervals in grey.

Figure 3. Forest plot of Composite score attention measures



Reported mean effect size and 95% credible intervals (black) for each study included in the meta-analysis. Estimated mean effect size and 95% credible intervals (grey) for each study. Overall effect size and 95% credible interval when all studies are combined.

5. Discussion

The present meta-analysis set out to assess the strength of evidence for an effect of mTBI on various attentional functions in community dwelling adults within three months of their injury. The literature search yielded mostly studies reporting measures of selective attention, and studies reporting a composite score of attention comprised of measures from the TMT A, the PASAT, the Stroop and the Digit-Symbol substitution test. Once the articles were selected, a robust Bayesian meta-analysis was conducted to quantify the extent of a meta-analytic effect while factoring in potential publication bias. This meta-analysis sought to fill a void for clinicians, many of whom want a more standardized view and reliable quantitative methods to assess attentional sequelae following mTBI. As such, the results of this meta-analysis addressed two main questions: (1) is there a meta-analytic effect for the impact of mTBI on selective attention, and (2) is there a meta-analytic effect for the impact of mTBI on attention as measured by the custom composite score? The choice of a Bayesian framework was based on, but not limited to, its ability to incorporate prior knowledge about the effect, to quantify evidence that the data provides along a continuum, distinguish between absence of evidence and evidence of absence without being dependent on an absent sampling plan, and the ability to remove the inherent bias against the null hypothesis that is present in null hypothesis significance testing (Wagenmakers et al., 2018). In addition, model averaging removes the need to select a single model in the event that uncertainty remains as to the presence of publication bias and heterogeneity (Bartoš et al., 2020).

With regards to selective attention, our resulting Bayes factor indicates extreme evidence for the presence of a meta-analytic effect and our associated effect size reveals a small to medium effect according to Cohen's *d* interpretation. However, inconclusive evidence for both heterogeneity and publication bias are noted. Given that the data has been taken from different studies which assessed selective attention with different tests, one might expect a certain degree of heterogeneity. However, this did not seem to be the case as evidenced by the consistent estimates of the forest plot (Figure 2). A few observations may elucidate why that is. Firstly, it may be that sampling from the same population, one that also shares similar durations since the injury, contributed to reduce a lot of the potential heterogeneity. Secondly, the different tests used may not have impacted the heterogeneity estimates significantly given that they all should be tapping into the same construct.

When investigating the studies that used a composite score of attention, the resulting Bayes factors indicates inconclusive evidence for a meta-analytic effect, heterogeneity, and publication bias. These results suggest that the composite score of attention used in the included studies did not provide support for the presence of an effect of mTBI on attention. While it is difficult to identify why a meta-analytic effect was not found, it is important to highlight that the results did not provide support for the null hypothesis either. One explanation for these inconclusive results could lie with the method itself. Using a composite score for the overall construct of attention is commendable as it can, as Mayer and colleagues (2009) claim, reduce the redundancy of among similar neuropsychological measures. However, inherent issues will be present as the tests included in this score can tap different attentional processes. For example, depending on which study is consulted, the Digit-Symbol substitution test is used to assess sustained attention, selective attention, or alternating attention (Munivenkatappa et al., 2016; Simpson & Schmitter-Edgecombe, 2000; Sohlberg & Mateer, 2001). Some processes may be differentially affected by mTBI and so combining measures on the sole basis that they are known as measuring "attention" loses a lot of the subtle impact mTBI has on attentional functioning. As such, inconclusive evidence with respect to such a score becomes understandable. What is clear though is that our overall findings seem to suggest that selective attention is impacted by mTBI in adults within three months of their injury and so is a worthwhile target for clinicians to attend.

5.1 Implications for research and clinical practice

While some studies point to a limited, if not absent, impact of mTBI on attention (Bélanger & Vanderploeg, 2005; Ponsford & Kinsella, 1992), our results seem to indicate that, as far as mTBI adult patients who have had an injury within three months are concerned, the available literature indicates that selective attention is impacted and should be addressed when establishing their cognitive profile. It is however difficult to corroborate our findings with a literature that is specific to selective attention given the vast methodological differences that exist from one study to another. However, not only did previous meta-analyses that investigated the cognitive sequela of mTBI on adults found a significant impact on attention (Bélanger et al., 2005; Lange et al., 2009) but many subjective complaints of attentional deficits are routinely voiced by the patients themselves (Sveen et al., 2013). Unfortunately, as previously discussed, the many variations in methodologies muddy the waters for clinicians who seek a definite answer for the specific processes of attention affected in an mTBI population. In response to this, the need for some type of standardized method to explore attentional functioning following mTBI would be beneficial to clinicians and researchers alike. We believe the following recommendations would help clear the waters. Firstly, we recommend that researchers avoid mixing TBI severities given that existing research shows that moderate-severe TBI cause larger impairments in cognitive functioning than mTBI (Schretlen & Shapiro, 2003). The subtleties in the sequela of the mTBI group may be lost if the sample contains a mixture of severities. Secondly, researchers should clearly state the theoretical framework of attention being used and the specific attentional process measured. For instance, stating that the Sohlberg and Mateer model of attention (2001) will be used informs the clinicians on the theoretical framework of the tests. If the PASAT is used for example, then, according to the stated framework, the researchers were using it to assess divided attention (Sohlberg & Mateer, 2001). In contrast, if the theoretical framework is not mentioned and vague terms like “Attentional function” or “Attention” are used, then the usage of the PASAT does not tell clinicians which attentional process to investigate if they do not have the tool in question. In addition, they might be pressed for time and so conducting a myriad of tests to evaluation “attentional function” could be impractical. Even though tests often tap into multiple domains (Bowden, 2017), a more comprehensive assessment of a given attentional construct in a research paper will still be beneficial to clinicians on the frontlines. Thirdly, efforts should be made to keep the time since injury consistent among patients. Since cognitive deficits have been reported to absolve by three months for most patients (Hiploylee et al., 2017), patients tested a few days after their injury can be drastically different than patients tested two or more months later. Fourthly, it is recommended to keep the cause of injury and the number of TBIs endured consistent among patients as both can impact performances (Merz et al., 2017; Sharbafshaaer, 2018). Different confounding variables can arise depending on the cause of injury. For instance, the presence of PTSD in veterans, or the mechanism of injury itself (blast vs. fall) can impact cognitive performance in different ways (Merz et al., 2017). In addition, effort testing should be conducted, if possible, to ensure the validity of the results. Finally, and most importantly, a clear definition of mTBI and more diagnostic information of the individuals in the sample being used, such as LOC, PTA, GCS, and whether the mTBI sustained is complicated or uncomplicated, should be included. Previous literature had noted that key indicators are often lacking (Ryu et al., 2009). This would help clinicians ensure that the findings of a study can be applied to their case. As previously mentioned, the realities of research are such that these recommendations are sometimes difficult to follow but we think it is a goal worth striving for as it will provide clinicians with better information when they must decide on what to assess and what to intervene on.

5.2. Limitations

The first limitation encountered was with the variety of attentional processes available in the current literature. Our initial objective was to explore various types of attention, such as divided, selective, sustained, but it was clear that the literature was sparse on such data for our target population. While we were able to explore the effects of mTBI on selective attention, this gap in the research hindered our ability to form conclusions on the many other processes that are routinely assessed in a clinical setting. Although the presented findings support an effect of mTBI on selective attention and found no evidence for or against the usage of the composite score to evaluate attention, some study design elements may have impacted the results. It can be argued that the sample size of studies that fit our selection criteria was small for both selective attention and the composite score studies. However, since Bayesian analyses do not assume large samples, analysis of smaller data sets can be conducted without losing power and while retaining precision (van de Schoot et al., 2015). In addition, a sensitivity analysis (robustness check; see appendix 1) was conducted to investigate if a larger sample size would affect our selective attention results and the findings, similar to our main analysis, revealed extreme evidence for the effect of mTBI on selective attention deficits. A prominent caveat for this meta-analysis would be at the methodological level, specifically the tools themselves. Not only do neuropsychological tests often measure multiple functions and processes concurrently (Bowden, 2017), the reliability of the tests used vary greatly. For instance, the technical manual of the TEA reports a test-retest reliability index of 0.86 for the Telephone Search subtest (Robertson et al., 1994). In contrast, the TMT A has an index of 0.55 (Strauss et al., 2006). As for the PASAT, its test-retest reliability varies from 0.83 to 0.96 (Strauss et al., 2006). In addition to these differences, the third condition of the D-KEFS Stroop task is reported to have reliability indices that vary with age groups. Specifically, for participants between the ages of 20 and 49, the index indicates 0.71, while it drops to 0.50 for individuals between the ages of 50 and 89 (Delis et al., 2001). This variability can add noise to any attempt of detecting subtle cognitive changes as reported in the first three months of mTBI. Furthermore, although the incentives for participants to display low effort was low given the research context, without effort testing, the validity of performances for the concerned studies remains unknown. This may have an impact on their effect size and, by extension, the findings of this meta-analysis.

5.3. Future Directions

Given the limitations of the present literature, many future directions exist to increase the breadth of information available to clinicians. Moving forward, it would be beneficial to explore the effect of mTBI on the other attentional processes as the research grows. As future research adds and labels measures of specific attentional processes in this population, meta-analyses that investigate the effect of mTBI on each type of attention can help inform clinicians in the assessment and rehabilitation phases of their patients. With proper support, clinicians would be better able to prioritize which processes to target if time is of the essence. Furthermore, using a Bayesian framework has many benefits that place it on the forefront of such research as the conclusions are more nuanced, provide a measure of evidence for a null result and can be continuously updated as more data becomes available (Wagenmakers et al., 2018).

Finally, many of the studies included in this meta-analysis were conducted one month after the initial injury. To further characterize patients, exploring the cognitive sequela at various times within the three months, as well as beyond this timeframe, could provide a clearer view as to the prognosis, the evolution, and the extinction of said deficits.

5.4. Conclusion

To conclude, our findings point to clear evidence for selective attention deficits in an adult mTBI population within three months of their injury. As for the usage of a composite score of attention, the data reflected inconclusive evidence. The question going forward is, given this evidence, how should we take care of patients? Given that the timeframe is within three months, readaptation might be unnecessary, however, psychoeducation and intervention programs may be beneficial. For instance, the *Sleep/fatigue Attention Anxiety Memory* (SAAM) intervention program, a low-cost, accessible, evidence-based mTBI intervention, might be an option as it targets four key symptoms after mTBI; sleep/fatigue, attention, anxiety, memory complaints (Audrit et al., 2020). Being applicable within four weeks and up to three months of the injury, the SAAM program consists of four sessions, each of which focus on one of the key symptoms. For example, the attention module is a 1h30 course that includes education and reassurance on these symptoms, information about steady return to everyday activities, the consequences of such symptoms (i.e. decision-making may become more difficult), strategies to change factors that influence attention, and problem-solving techniques. By integrating reinforcement, realistic goal selection, practical advice, exercises, active listening, and reassurance, SAAM aims to educate, empower, and help mTBI patients to better manage their symptoms and gradually resume their activities.

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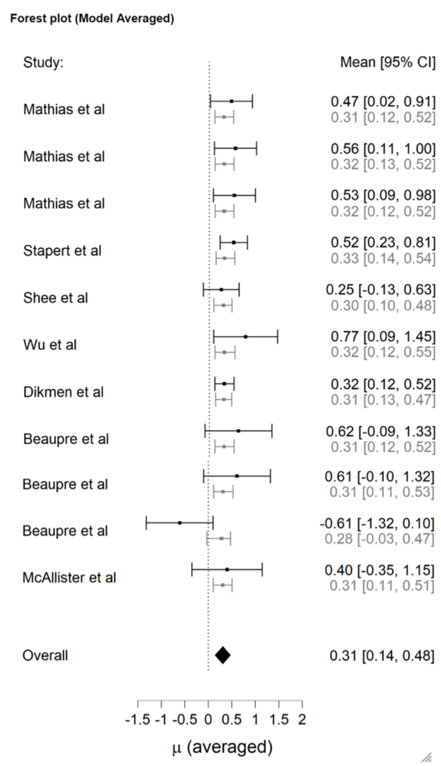
Appendix 1

Robustness Check (Sensitivity analysis)

For the main analysis, we chose to select a single estimate of selective attention from each study to avoid violating the independence of estimate assumption. However, it can be argued that by doing so, we omit potentially valuable data. As such, we conducted a robustness check using all selective attention measures (n = 11) available to investigate whether the conclusions were still supported regardless of the approach used. Our findings revealed that the posterior distribution show that the most likely models also contain an effect. When sets of models were compared, the inclusion BF demonstrated extreme evidence in support of the presence of an effect (BF_{10} = 201.91) but weak evidence was found to support the presence or absence of heterogeneity (BF_{τ} = 0.40). Interestingly, there was moderate evidence for the presence of publication bias (BF_{ω} = 8.12). The meta-analytical conditional effect size estimate was found to be *d* = .312, 95% *CI* [.146, .482]. Figure 4 shows the forest plot with the calculated effect sizes for each study and their credible intervals in black, along with the estimated effect sizes and their credible intervals in grey. While the Bayes factors vary from the initial analysis, this is to be expected given the additional evidence factored into the model. Despite the difference, there is a clear indication of the presence of the effect in both cases.

Figure 4. Forest plot of all available selective attention measures (Robustness check)



Reported mean effect size and 95% credible intervals (black) for each study included in the robustness check. Estimated mean effect size and 95% credible intervals (grey) for each study. Overall effect size and 95% credible interval when all studies are combined.