Long-Term Consequences of Mild Traumatic Brain Injury in Younger Adults on Cognitive Performance and Emotional Regulation: Comparisons with Older Adults

by

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Concussions, or mild traumatic brain injuries (mTBI), are common and seemingly innocuous. However, even long after individuals experience a mTBI they often report psychological consequences such as fatigue, unstable mood, and poor concentration. Individuals with a history of mTBI also often complain of difficulties in focusing attention, and lingering memory problems, though documenting deficits using standard neuropsychological testing typically fails to corroborate these effects. Many of their cognitive complaints are also voiced by typically aging older adults. Given this, we examined whether the cognitive signatures in aging and in those in young adults with a remote mTBI would be similar. We predicted a memory deficit relative to young adults with no mTBI history, on a recognition test for pairs of unrelated words (Associative memory) but not on an easier recognition test for individual words (Item memory) due to predicted deficits in available cognitive resources. We also predicted that deficits would be greater when encoding was done under conditions of reduced attentional resource availability, known to negatively affect older adults, and likely to exacerbate cognitive and psychological symptoms in mTBI. Data for Experiment 1 were collected in an in-person sample. Experiment 2 followed the same design, but data were collected in an online sample using crowd sourcing. Participants were asked to study pairs of unrelated words under either full or divided attention conditions. We found the expected main effect of Test Type on recognition memory, in both experiments, with Associative memory being poorer than Item memory. Moreover, we found the expected main effect of Attention with memory being poorer when encoding was done under divided attention. In terms of cognitive performance, we replicated the known 'associative memory deficit' in our older adult sample in Experiment 1, but not 2. We found that the drop in recognition accuracy from full to divided Attention conditions on the Associative memory test was significantly greater in mTBI compared to young controls and was like that seen in older adults. In terms of psychological measures, we found that self-reported mental fatigue increased significantly, only in the mTBI group, as performance on the Associative test under divided attention decreased. In conclusion, our findings suggest that younger adults with a

remote mTBI, like older adults, have a tougher time coping when tasks increase in cognitive demand. Cognitive tasks may be experienced as more demanding in those with a mTBI group, even months after injury.

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Chapter 1
Introduction

1.1 Background

Traumatic brain injuries (TBIs), a blow to the head from a variety of sources (i.e., sport collisions, car accidents, falling, etc.), have been colloquially referred to as the *silent epidemic* due to the fact they are chronically under reported and unrecognized (Goldstein, 1990). However, they are a major cause of disability, morbidity, and death, presenting a significant public health concern. It is reported to have a lifetime incidence rate of 246 per 1000 individuals in the United States (Veliz et al., 2021). With the Center of Disease Control and Prevention estimating an annual incidence number of 2.8 million (Taylor et al., 2017). In Canada, this number is harder to determine as many approximations are extrapolated from incidence rates from the United States. Though, a recent estimate by Langer et al. (2020) has put the figure around 150,000 annually in Ontario alone. This number has steadily increased nationally in the United States and Canada in the previous two decades and is suspected to be a result of greater brain injury awareness and improvements in reporting and recognition of injuries, especially within the domain of sport (Capizzi et al., 2020; Gordon & Kuhle, 2022).

TBIs are categorized into three levels of severity: from mild, moderate, or severe. It is important to note most cases are classified as mild, with estimates ranging from around 70% to 90% of all cases being mild (Civilian sample: Cassidy et al., 2004; Military sample: Farmer et al., 2017), though this number has reached upwards of 95% (Feigin et al., 2013). Severity is regularly determined by Glasgow Coma Scale (GCS) scores (Teasdale & Jennett, 1974) within 24 hours of injury. The GCS assesses ocular, oral, and motoric responses and

comprises a score between 3 and 15, with classifications as: severe GCS ≤ 8, moderate GCS 9-12, and mild GCS ≥ 13 (Teasdale & Jennett, 1974). As well, this number is thought to be underestimated due to established diagnostic biases, such that, patients with mild TBIs rarely seek medical care and are not often admitted into hospitals. This has led to a dominance of research findings pertaining to TBIs being reliant on findings in moderate to severe TBI patients. For one, moderate and severe patients have a more complete diagnosis, frequently accompanied with a GCS score, unlike mild cases. Likewise, they have been shown to have more conclusive brain lesioning and subsequent greater and more frequent cognitive and behavioural complaints (see Vakil et al., 2019 for a review).

Those with a history of mTBI frequently complain of difficulties with attention, and lingering memory problems that can perseverate beyond the acute stage of injury and into the chronic period (>3 months post injury) (see review by Belanger et al., 2005). Though, standard neuropsychological testing has revealed subtle (Vanderploeg et al., 2005) or even mixed findings for the presence of deficits (Chen et al., 2004; Frencham et al., 2005; Rohling et al., 2011). It is theorized that a lack of group differences could be explained by insensitive testing and mean-level analyses that make it difficult to find substantial differences in mTBI samples. Additionally, these samples are frequently heterogeneous, with a wide variety of symptomology and injury history (Eierud et al., 2014; Tellier et al., 2009). The inconsistency between subjective reports and standard neuropsychological testing presents a challenge to health care professionals and insurance companies, as it stirs up debate about the necessity of treatment and the severity of complaints. These individuals have also been labelled as the ‘miserable minority,’ where persistent and disturbing affective and cognitive symptoms

continue to be experienced months and years later well into the chronic phase of injury (Dikman et al., 2017; Ponsford et al., 2000; Ruff et al., 1996; Sigurdardottir et al.; 2009, Theadom et al., 2016).

A population that shares many of the same cognitive complaints as mTBI patients are healthy aging older adults. Older adults with no history of head injury and young adults with a history of head injury have both independently shown impairment on cognitive tasks that require executive functioning (Bopp & Verhaeghan, 2005; Park et al., 2002; Salthouse & Babcock., 1991). This may be explained by the shared vulnerability of the frontal lobes to both aging (Cabeza & Dennis, 2013; Prull et al., 2000; Raz et al., 2004) and TBI (Mattson & Levin, 1990; Witt et al., 2010) and has been suggested to explain why these two populations may share a similar cognitive profile, particularly for prefrontal-mediated tasks. Additionally, older adults experience episodic declines suggested to be caused by a reduced ability to bind new information (words, scenes, images) to another piece of information or context (Chalfonte & Johnson, 1996; Mitchell et al., 2000). Naveh-Benjamin (2000) proposed the associative memory deficit, where there is a deficit in their ability to create and retrieve links between single items of information. In parallel, young adults with a chronic history of mTBI have demonstrated similar associative deficits for items when presented within scenes or for category-exemplar pairs, particularly when attention was divided during the encoding phase (e.g., Blanchet et al., 2009: Mangels et al., 2002). However, neither of these studies examined memory using the traditional associative memory format of unrelated word pairs. As such it is difficult to know if these reported deficits are specific to the paradigms used, or whether they represent true associative memory deficits in mTBI. One of the primary goals

of this thesis is to explore potential parallels between mTBI and older adults using the traditional paradigm for assessing the associative deficit hypothesis in aging. Specifically, comparing memory for individual items and their associations using unrelated word pairs.

Finding a unique cognitive signature for mTBI has thus far been elusive, and merging both research on aging and brain injuries could show a shared profile between healthy aging older adults and individuals with mTBI. Both populations share similar cognitive complaints and have parallel vulnerabilities in frontal and temporal lobe connectivity. This thesis is organized into two separate experiments designed to examine the long-term sequalae of memory in mTBI and the similarities and differences with older adults. Chapter 2 will consist of data collected through an in-person study run at the University of Waterloo with undergraduate students with and without a history of mTBI. Additionally, older adults from the Kitchener-Waterloo region were included through a community outreach program that recruits older adults (65+ years old) to participate in research conducted at the University of Waterloo. In Chapter 3 a parallel study was conducted online using the crowdsourcing platform Prolific (www.prolific.co, London, UK). Participants were recruited from various countries including Canada, United States, Ireland, United Kingdom, New Zealand, and Australia and completion was done entirely remotely without experimenter involvement. In Chapter 4 I discuss the key findings from this thesis and their implications.

1.2 Mild Traumatic Brain Injuries (mTBI)

1.2.1 mTBI Definitions

The primary difficulty with analyzing and researching mTBIs is the extensive range of definitions applied to what is and is not considered a mTBI (see Ruff et al., 2009 for review). An analysis by the World Health Organization (WHO) found 38 unique definitions/terms throughout the literature for what could be considered an mTBI (Carroll et al., 2004). The two most frequent terms have been mTBI and concussion and their use are usually dependent on the context. Often, concussion will be used to describe a head injury in the field of sport and sport medicine, whereas mTBI is most frequently used in general medical and scientific reports. Occasionally, the terms mTBI and concussion are used interchangeably, though recently there has been a shift to better characterize TBI incidents into their range of severity. For the purposes of this thesis the term mTBI will be used throughout to describe individuals who have sustained a head injury.

The difficulty of categorization is not limited to terms but also to the diagnostic criteria for TBI severity. The American Congress of Rehabilitation Medicine (ACRM) was the first interdisciplinary group to provide a diagnostic criterion for mTBI. They defined an mTBI as a traumatically induced physiological disruption of brain function as manifested to including one of the following: loss of consciousness (LOC), post-traumatic amnesia (PTA), alteration of mental state at time of accident (e.g., feeling dazed, disoriented, or confused), and focal neurologic deficits that may or may not be transient. Additionally, criteria to be considered mild severity is that LOC most not exceed 30 minutes, PTA must not exceed 24

hours and a GCS must be between 13-15 (American Congress for Rehabilitation Medicine, 1993).

At the turn of the century the WHO (Carroll et al., 2004) designated their own task force in response to a lack of clear definitions being used for TBIs in the literature and expanded upon previously understood definitions. They defined mTBI as ‘an acute brain injury resulting from mechanical energy to the head from external physical forces’ with an operational criterion for clinical diagnosis including: 1) one or more of the following: confusion, loss of consciousness for 30 minutes or less, post-traumatic amnesia for less than 24 hours, and/or other transient neurological abnormalities such as focal signs, seizure, and intracranial lesion not requiring surgery ; 2) GCS score of 13-15 after 30 minutes post-injury or later upon presentation for health care (p. 115). Moreover, any manifestations must not be due to drugs, alcohol, medications, or injury caused from a secondary injury or treatment or caused by any other problems such as psychological trauma or language disorders (Carroll et al., 2004).

As discussed by Ruff et al. (2009), even with a clear definition the largest challenge to mTBI research is that many injuries are not evaluated by a physician at the time of occurrence or are evaluated months to years after injury. One of the focal points is the inclusion of LOC, especially when assessment is self-reported. LOC is an important symptom to account for since it has been demonstrated to exacerbate brain connectivity issues compared to when consciousness is not lost. In a diffusion tension imaging study by Sorg et al. (2014) they found mTBI with LOC were more likely to exhibit executive functioning problems compared to mTBI without LOC or controls. Acute symptoms such as

post-traumatic amnesia and confusion that are required for clinical diagnosis potentially persist beyond any LOC. This presents a problem when self-reporting because of their cognitive state potentially impairing their ability to accurately remember there was a LOC. For example, a patient may claim they woke up from a LOC but, were conscious the entire time and were amnesic. Moreover, Tellier et al. (2009) showed that when they grouped their sample based on GCS scores there were no differences, but when their groups were redefined based on PTA there were differences. These examples highlight the heterogeneity problem that can arise from generalizing mTBI severity. Unfortunately, there has not been a uniform definition of mTBI that has been applied across disciplines, resulting in a heterogeneous diagnostic criterion across the literature (Ruff et al., 2009). Together, the WHO and ARCM definitions share many overlapping qualities and emphasize the importance of documenting, as accurately as possible, the characteristics of each participant's injury history (e.g., PTA, LOC, confusion, disorientation, etc.). In Chapter 2, 42% (n = 15) of the mTBI conformed to these criteria, while in Chapter 3, 63% (n = 22) conformed to these criteria. Based on the WHO and ARCM definitions the remaining participants could be considered subclinical mTBI.

1.2.2 Neuropathology of mTBI

A mTBI is a closed-head injury that occurs from external forces that result in neuropathologic disruption. Additionally, TBIs are traditionally composed of both focal and/or diffuse injuries, with many incidents containing injury of both varieties, especially if they are more severe (Mckee & Daneshvar, 2015). A focal injury occurs when there is a

physical compression applied to skull and underlying tissues, and can include various complications such as lesioning, subdural, or epidural hematomas, and hemorrhaging. These primarily occur from the initial linear impact of the brain hitting the inside of the skull from an abrupt deceleration (*coup*), followed by the inertia of the brain hitting the opposite side of the skull (*contrecoup*) (Shaw, 2002). The frontal and temporal lobes are most vulnerable to the coup/contrecoup injuries (see Kim & Gean, 2011, for review of imaging and intracranial injury), especially the dorsolateral prefrontal cortex (see Eierud et al., 2014 for comprehensive review), which is an important region for working memory (Petrides, 2000). The rough and jagged nature of the internal geometry of the skull around the orbits and cranial nerve processes make the orbitofrontal and anterior temporal regions also particularly susceptible to injury (Mattson & Levin, 1990).

The diffuse injuries have become the more primary focus to mTBI researchers and are suggested to be, at least partially, responsible for behavioural and cognitive complaints. A diffuse injury is composed of axonal injury (such as sheering and cutting of axons), disruption of white matter tracts, and hypoxic-ischemic injuries (because of LOC). These injuries occur from the axon bundles becoming twisted and/or sheered, and intracranial pressures increasing from widespread swelling and rupturing of blood vessels (Mckee & Daneshvar, 2015). White matter axons are more prone to damage caused by rapid acceleration and deceleration due to the linear arrangement of microtubules and neurofilaments. The axon membrane and axoplasm have a large surface to volume ratio, which further increases risk of complete axon transection (Johnson et al., 2013; Mckee & Daneshvar, 2015).

It has been established that these repetitive impacts to the head lead to a dramatic increase in the occurrence of chronic traumatic encephalopathy (CTE), a progressive and fatal degenerative brain disease (Mckee et al., 2018). Though not a focus of the current thesis it is important to understand the longer-term implications of head injuries. CTE was first recognized over a century ago as an issue arising in boxers, known then as 'punch-drunk syndrome' (Martland, 1928). Though, it took a century later, until 2022, for the US National Institute of Health to fully acknowledge the causal link between hits to the head and the development of CTE. The issue has become a pivotal topic in the realm of sport and has led to recent lawsuits by former players against large professional leagues, such as the National Hockey League and National Football League. Recently, the goal has now shifted to exploring the chronic phase of injury and studying factors that are contingent to the later progress of neurodegenerative disease such as CTE (Mckee et al., 2013).

In conjunction with studies looking at behavioural markings, researchers have been on the search for physiological markers of mTBI as well. Conventional imaging techniques such as computed tomography (CT) and functional magnetic resonance imaging (fMRI) have produced mixed findings of differences between healthy controls and mTBI patients. One more advanced technique that has been shown to be more dependable in mTBI imaging is the use of diffusion tensor imaging (DTI). DTI is a technique that measures the water diffusion within the brain and is primarily used to measure white matter tractography. This is especially relevant to mTBI because of the cutting and shearing of axons because of injury. Imaging studies have shown traumatic axonal injury (TAI) primarily found in the frontal lobe (Einarsen et al., 2019). White matter integrity in the frontal lobes is important to several

cognitive functions and is primarily associated with executive functioning and working memory, which are important to the contribution of episodic memory, particularly in using encoding strategies, and incorporating temporal and contextual information (Dickerson & Eichenbaum, 2010; Moscovitch, 1994).

As discussed earlier, the temporal lobes are also in a vulnerable position to be affected from the forces applied to the head. Imaging has shown atrophy and compromised white matter in the medial temporal lobe, particularly the hippocampus and fornix (Mild-Severe: Tate & Bigler, 2000; Mild: Umile et al., 2002) and midline structures (i.e., cingulate gyrus, corpus callosum, thalamus, lateral ventricle) (Mod-Severe: Yount et al., 2002). The hippocampus, and its output structure the fornix is at risk because of the fornix connection to the septum pellucidum, the membrane that separates the right and left lateral ventricles. The septum pellucidum is exposed to tearing from the mTBI forces being applied to the cerebrospinal fluid (CSF) inside the ventricles (Bigler, 2023). The hippocampus is also sensitive to excitotoxicity effects that can be caused from the stress response to injury (Bigler, 2023). Direct studies of medial temporal lobe tractography and volume have been limited thus far, but some recent studies have shown volumetric decreases and hippocampal atrophy (e.g., Misquitta et al., 2018; Monti et al., 2013; Singh et al., 2014), while others have not shown differences in young samples (e.g., Wilke et al., 2018). A major limitation of these studies is the influence of age, with many recruiting former athletes' decades after their career and differences being compromised by natural atrophic aging effects of the medial temporal lobe (see Bigler, 2023 for review). Additionally, participants are often former

contact sport (e.g., football, hockey, rugby, etc.) athletes who have sustained multiple head injuries over the course of their career from repeated head impacts.

1.2.3 Long-Term Neurocognitive and Emotional Deficiency in mTBI

The acute cognitive effects of mTBI have been well documented, however, the long-term sequalae on neurocognitive and emotional impairment has been less recognized. It was initially estimated that only around 15% of cases of mTBI have persistent symptoms that are maintained through the acute phase (< 3 months post-injury). However, a recent review by McInnes and colleagues (2017) found that this number is severely underestimated, even when looking at participants with a single mTBI. In their review they found that 46% of participants were cognitively impaired at 3 months, 61% at 6 months, 48% at 12 months, and 88% at > 12 months post injury (p.10; note these values are variable due to the limited nature of research further beyond injury). They also echoed concerns about cognitive impairment being uniformly underdiagnosed because of insensitive or improper neuropsychological testing (McInnes et al., 2017).

Acute psychiatric disturbances, such as depression and anxiety have been understood to occur immediately following injury, though the etiological mechanisms and long-term impacts are less understood (van der Horn et al., 2016). Major depressive disorder is a primary concern post-injury, and a recent meta-analysis by Hellewell et al. (2020) found that chronic mTBI had over a three times higher risk of developing depression, even long after injury. A review by Rao & Lyketsos (2000) found the most frequent symptoms post injury (6-24 months) were dysphoria, fatigue, irritability, and anhedonia, while approximately 25%

experienced major depressive episodes. This increased risk is theorized to be the result of physiological, psychological, and environmental changes following the injury.

Stress responses activate key brain structures, such as the hypothalamus, amygdala, and insula, which are involved in the sympathetic autonomic nervous system response and hypothalamic-pituitary-adrenal (HPA) axis (the major endocrine stress axis). Sustaining a head injury, and coping with any long-term cognitive repercussions, produces a lot of stress on the body. Studies have shown HPA axis dysfunction and interactions with cortisol in acute (e.g., Musacchio et al., 2023) and chronic stages of injury (e.g., Sojka et al., 2006), though some studies have found no differences between mTBI and controls (e.g., Spikman et al., 2021). Cortisol stress responses are well-documented to influence functionality of the hippocampus, amygdala, and prefrontal cortex (Dedovic et al., 2009), important structures to memory encoding and consolidation.

The etiology of emotional complaints is complicated and has been suggested to be caused by a myriad of reasons. For one, the physical injury can cause neural disruption and connectivity issues primarily to brain structures involved in the stress response. Alternatively, sustaining a head injury is accompanied with many external stressors that can elevate cortisol levels for a prolonged period. For example, a university student may endure a mTBI that removes them from their courses for a prolonged period. This presents challenges to them academically, socially, and emotionally, and requires an adequate emotional response to cope. Thus, advancing our understanding of the long-term impacts of emotional regulation in mTBI is important in reducing the impact of these challenges.

As discussed, the prefrontal cortex is particularly vulnerable to mTBI and serves a primary role in the cognitive control of emotions (Oshsner & Gross, 2005). Microstructural changes in key white matter structures along the emotional regulation tract have been found. In a longitudinal tractography study, van der Horn et al. (2021) found changes in emotional regulation tracts in symptomatic mTBI compared to uncomplicated mTBI and healthy controls when measuring primary tract structures such as the forceps minor, uncinate fasciculus, and cingulum bundle. Additionally, Chen et al. (2009) showed hypoactivation in the dorsolateral prefrontal cortex in depressed athletes with mTBI, showing that pathophysiological changes may account for these affective complaints. Overall, these structures play key roles in the communications between frontal lobe and limbic system in the limbic-frontal model of depression.

Fatigue has been identified be more severe and more prevalent in TBI one-year post-injury (Cantor et al., 2008), and much like affect its causes appear to be a combination of physiological (i.e., neuroendocrine abnormalities), psychological, and social influences. Though, pathological fatigue in many neurological disorders is suggested to be related to key structures such as the basal ganglia, thalamus, amygdala, and prefrontal cortex, which are impacted in mTBI (Chaudhuri & Behan, 2004; Johansson, 2021). Studies have used response time as a proxy for assessing fatigue and have found differences in mTBI compared to controls when completing cognitively demanding tasks (e.g., Acute stage (2 months): Anderson & Cockle, 2021; Chronic stage: Möller et al., 2017; Johansson & Rönnbäck, 2015). Limited studies have assessed self-reported levels of fatigue before and after a cognitive task, within the same person. In one study that did look at this, Berginström and

colleagues (2018) asked a TBI (70% of sample was mild) and healthy control group to complete a fatiguing 27-minute attention task while in a fMRI scanner. They showed a higher self-reported change in fatigue (from before to after the task) in the TBI group compared to controls. They additionally showed that this change was associated with altered striato-thalamic-cortical functioning (Berginström et al., 2018). These findings all contribute to the idea that long-term psychological and emotional consequences persist in mTBI into the chronic stage of recovery. Current studies, however, rarely measure fatigue, irritability, or mood, following cognitive task performance. It may in fact be that these are precisely the measures needed to differentiate mTBI from controls and may be the key factor differentiating mTBI from older adults who share similar cognitive complaints.

A primary contribution of the present thesis is to explore the effects of cognitive stress on state levels of affective response in a group of individuals who experience a remote mTBI versus no mTBI. To our knowledge, no other previous study has implemented a pre-post assessment of affect to assess differences between mTBI and controls on subjective self reports when completing cognitively demanding tasks. Additionally, only a limited number of studies have directly explored fatigue in a pre-post paradigm. In the current thesis, affect was directly investigated (positive and negative), while also examining participants' levels of fatigue and irritability following completion of demanding cognitive tasks.

1.3 Older Adults

1.3.1 Cognitive Aging

Memory is not a single entity, rather there is a combination of neural networks that mediate distinct types of memory. Aging has a more detrimental effect on certain types of memory compared to others. Our procedural memory, or the ability to perform learned actions and skills such as riding a bike, remains intact as we age. Moreover, semantic memory, or the ability to remember general knowledge about the world (e.g., Paris is the capital of France), also remains intact in healthy aging older adults. These memory facets remain intact with healthy aging, whereas deterioration would be associated with neurological or neurocognitive disorders (e.g., stroke, dementia, etc.).

In contrast, working memory, or the ability to hold and manipulate short bits of information, shows a decline with age (Park et al., 2002). These age-related differences appear when the task becomes more demanding and information that is being held must be manipulated. For example, reading a list of city names and asking participants to repeat them back in alphabetical order would show age-related deficits (Craik, 1990). However, the ability to simply hold information declines little with age. If you were to ask a group of participants to repeat a short series of digits back to you or repeat a sentence, they would be successful, regardless of age.

Episodic memory, the ability to remember personal events and experiences, is another type of memory that is negatively affected by aging. In fact, episodic memory shows the greatest age-related difference in performance levels (see Nyberg et al., 2012 for review). Moreover, age-related differences are exacerbated when memory is required without the help

of cues (i.e., on tests of free recall compared to recognition; Perlmutter, 1979), when learning and remembering associations between items (e.g., differentiating intact pairings of items versus recombined ones; Naveh-Benjamin, 2000), or when memory is for prospective information (e.g., remembering to make an appointment; Henry et al., 2004).

1.3.2 General Theories of Cognitive Decline in Aging

Researchers have proposed several theories as to why some cognitive processes show a decline with age. Here, I will outline four of the major theories proposed to explain the deficits in memory detail and quantity. The theories are relevant to discussion in my thesis because they provide the mechanistic basis for declines in memory associated with aging. Many of these theories are formulated based on impairment to prefrontal mediated functions that result in a decline in general episodic and working memory quality. It may be that one or many of these theories can be applied to the mTBI group based on the idea that the two groups share some similar neurocognitive complaints.

One of these theories, the *Processing-Speed* Theory was proposed by Salthouse (1996). This theory rests on the idea that aging is associated with a decrease in the speed in which cognitive operations can be executed, and that this speed decline is responsible for the quality of cognitive processing in two ways. The first, is the *limited time* mechanism, where relevant operations cannot be successfully performed in time and the cognitive operation fails. This is the result of early operations taking a considerable proportion of time, restricting later operations from being performed effectively. The second, is the *simultaneity mechanism*, where relevant information from early-stage cognition are lost and no longer

available when later operations move downstream. Processing deficits could therefore occur from the disconnect of information when performing critical operations (Salthouse, 1996).

Another proposed rationale is a reduction in the attentional resources available to complete cognitive tasks. Craik & Byrd (1982) proposed that humans have a *mental energy* store, in what they define as being analogous to physical energy. That is, there is a reservoir of mental energy that is consumed when completing demanding and taxing cognitive tasks. Mental fatigue begins to onset when this reservoir is drained. They suggest that older adults have a reduction in available resources, leading to greater difficulty when attempting novel and strategic memory processes (Craik & Byrd, 1982). However, not all effects of aging are replicated when reducing attentional resources in younger adults (e.g., such as performing a second task at encoding or retrieval). Thus, age-related declines are linked to additional factors beyond attentional resource management (Luo & Craik, 2008).

Hasher & Zacks (1988) suggested the *inhibition* theory, the idea that specific working memory deficits are caused by ineffective inhibitory mechanisms. According to their theory, inhibitory mechanisms act in two ways. First, the mechanism is responsible for filtering and preventing irrelevant information from entering working memory. Second, the mechanism is important for deleting undesired or irrelevant information from working memory. Thus, they define inhibition as both restraint and deletion, whereas in the literature inhibition has often been associated only with restraint (Hasher & Zacks, 1988; Lustig et al., 2007).

The final theory is Jacoby's (1991) process dissociation framework, which is built on the foundation that there is an automatic or unconscious influence on memory processes. Jacoby differentiated recollection memory from familiarity, where the former is a

consciously controlled form of memory use, while the later is an automatic type of memory use without conscious influence. Aging is associated with declines in this consciously controlled memory, while the automatic type of memory remains.

It may be true that all these theories play a role in the cognitive decline of aging. Within the framework of my thesis, I am unable to make compelling arguments for or against these theories, but instead consider them as a possible mechanistic explanation for age-related differences and the proposition of a parallel explanation in mTBI.

1.4 Associative Memory

1.4.1 Associative Memory Deficit

The memories that we make are not singular moments stored and replayed as they were experienced; rather they are a reconstruction. This reconstructive process incorporates the linking of individual aspects such as items, contexts, and timing information (Tulving, 1972). For example, we may recall meeting a new friend at a party last week. In this scenario, we can reconstruct this event by linking important aspects to create a high-quality episodic memory of our encounter. These memories encompass what is known as *Associative memory*, or the ability to encode and retrieve the relationship between unrelated items or contexts. However, sometimes our memory is void of these contextual details, yet we can recall a central piece of information. In this case, we may remember meeting this new friend but cannot recall how or when we met them. These memories form our *Item memory*, or the ability to encode and retrieve single items without accompanying item information. Identifying factors that hinder these memories, as well as the neural substrates underlying

recollection of high-fidelity ones, is important to both psychological science and society at large.

A substantial amount of research has shown that associative memory is memory for the relations between two or more items (e.g., word-word, face-name, object-scene, word-category). It has also been shown to be a more demanding task than item memory (Castel & Craik, 2003; Gold et al., 2006; Kilb & Naveh-Benjamin, 2007; Naveh-Benjamin, 2000; Overman & Becker, 2009; Yonelinas, 1997; Yonelinas et al., 2007). This variability in difficulty has been suggested to occur because of the differences in memory support. Item memory is supported by *both* recollection and familiarity, whereas associative memory relies primarily on recollection (Hockley & Consoli, 1999; Yonelinas et al., 2007). This added help of familiarity (or gist-based memory, see Tulving, 1985) provides support when richer, qualitative details are missing.

1.4.2 Neural Basis of Item and Associative Memory

Associative memory is believed to be primarily reliant on the medial temporal lobe and its functionally connected cortical areas. More specifically, these rich contextualized memories of past events are believed to be reliant on the functional relationship between the hippocampus, para-hippocampal region, neocortical regions, and prefrontal cortex (Allen & Fortin, 2013). A key finding is that structures within the medial temporal lobe, particularly the hippocampus, have distinct functions in combining information from multiple cortical streams (Dickerson & Eichenbaum, 2010; Moscovitch et al. 2016). Popular theories of memory function (Aggleton & Brown, 1999; Diana et al., 2007; Eichenbaum et al., 1992)

suggest a division of labour occurs in the brain such that the hippocampus disproportionately supports recollection of contextual information associated with the item (known as binding, Yonelinas, 2013). We know selective damage to the hippocampus, or deterioration compromises memory of past episodes which are reliant on one's ability to link or bind unique features making up an event (Hassabis & Maguire, 2007; Squire & Zola, 1998). Another nearby brain region, the perirhinal cortex, instead supports memory that is based on familiarity, or memories based on gut feelings that lack identifiable details (Brown & Aggleton, 2001). Further findings from functional magnetic resonance imaging (fMRI) have shown associative memory relies on hippocampal activity, while item memory is connected to para-hippocampal activity. Further reports have shown greater prefrontal cortex recruitment for associative compared to item memory (Blumenfeld et al., 2011; Brehmer et al., 2020; Lepage et al., 2006; Staresina and Davachi, 2008; Westerberg et al., 2012). This is particularly relevant to the current thesis as aging and mTBI are both linked to executive-type, or frontal-lobe type deficits in correctly linking items together.

1.4.3 Associative Memory Deficit in Older Adults

Of particular interest to my thesis is the decline of episodic memory, specifically memory for items (*item* memory) and their associated information (*associative* memory). As previously mentioned, associative memory is more demanding than item memory. As individuals get older their associative memory starts to show decline compared to their young adult counterparts (Chalfonte & Johnson, 1996; Naveh-Benjamin, 2000). Yet, their memory for an individual item is comparatively well preserved. This phenomenon has been termed,

the *associative memory deficit hypothesis* (see Naveh-Benjamin, 2000). The associative memory deficit has been demonstrated across many empirical studies using varied materials (e.g., word-word, face-name, object-scene combinations; see Old & Naveh-Benjamin, 2008 for review). The decline in associative memory has been suggested to be linked to the age-related deterioration in the hippocampus and in the prefrontal cortex (Raz et al., 2005). Becker at al. (2015) demonstrated that better associative memory in older adults has been linked to larger grey-matter volume in the prefrontal cortex when learning of associations was intentional.

1.4.4 mTBI and Associative Memory

Like older adults, individuals who have sustained a traumatic brain injury (TBI) also suffer from structural and functional changes in localized brain regions. However, as it pertains to my thesis, only two studies to date have assessed associative memory in mTBI. Unfortunately, the samples sizes were quite small, though the studies' connections to local hospitals did allow for greater characterization of each participant with a more comprehensive neuropsychological and injury history profile than is available in the present thesis. These common neurological changes suggest the two groups may share common cognitive profiles, with mTBI showing primarily associative rather than item memory deficits.

The first study by Mangels et al. (2002) recruited three separate groups of participants: controls (n = 10), mTBI (n = 11), and severe TBI (n = 13), with the TBI groups consisting of individuals who were approximately 3-4 years post-injury. Participants were

asked to study scene-object pairs under either full or divided attention using a digit-monitoring task (within-subject). They later assessed memory for these objects in one of three ways: free-recall (list as many objects as you remember); scene-cued recall (list as many objects as you remember *with this scene*), and recognition (old/new recognition, if old choose the scene it was paired with). They found for free recall that mTBI and controls only differed when encoding was performed under divided attention. Conversely, there were no differences in memory when recall was cued with a scene. The mTBI and control groups did differ in recognition memory, but again, only when initial encoding was divided, with the control group having a higher corrected recognition score. The authors concluded that any memory deficits in the mTBI group were secondary to deficits in executive control since differences were only found when dual tasking was required. Moreover, deficits in the mTBI group were milder when compared to the severe TBI group. The rationale was that mTBI may not be severe enough for more pronounced memory deficits to be detected, but that their cognitive functioning is 'fragile' enough that the introduction of having to dual task put a strain on their already lower cognitive resources (Mangels et al., 2002). Interestingly, both the mTBI and severe TBI group performed significantly better than controls on the task used to divide attention (the digit monitoring task). It might be that the TBI groups were prioritizing the digit task, rather than the memory tasks, accounting for their poorer memory scores. Thus, one of the shortcomings of their findings is that each group prioritized different tasks during the divided attention conditions. The main finding of group differences can be called into question since the mTBI group was more proficient in the secondary task, while the authors only examined the primary task performance.

The second study by Blanchet et al. (2009) was inspired and built upon the study by Mangels et al. (2002) and followed a similar paradigm. They recruited healthy controls (n = 12) and individuals who had experienced a mTBI (n = 13) between 4 months to 8 years ago. They instructed participants to learn category-target word pairs under full and divided attention conditions (within-subject). The change to words in this study, rather than scenes in the Mangels et al. study, was done to make the task more difficult and increase sensitivity of the test for detecting group differences. Paivio's dual coding theory (1991) suggests that pictures are more memorable than words by providing additional environmental supports, which facilitate easier recollection. Given this, the Mangels et al. study may not have been challenging enough to fully highlight group differences.,. Additionally, in the Blanchet et al. study, environmental support at retrieval was manipulated by including a variety of memory assessments: free recall of target words, cued recall (shown category and asked to freely recall target words), and recognition (old/new recognition, if old did you see this target word with this cue). As well, they included semantically related and unrelated pairing as the latter requires more elaborative encoding strategies than semantically congruent words (Naveh-Benjamin et al., 2003), and may be more sensitive to group differences. Like Mangels et al. (2002), they found the mTBI group recalled and recognized fewer target words when pairs were encoded under divided attention, regardless of retrieval test type or semantic relatedness of the pair. They concluded that the learning of verbal items under divided attention is impaired in mTBI, and that reduction of cognitive resources result in a diminished attentional capacity, accounting for the pattern.

1.5 Thesis Rationale

The primary consideration of the present thesis is to build on the previous studies, but to assess item and associative memory using a traditional paradigm adapted from the literature on associative deficits in older adults (see Experiment 2 in Naveh-Benjamin, 2000). The previous studies (i.e., Blanchet et al., 2009; Mangels et al., 2002) comparing controls to mTBI primarily looked at item memory within a context of associations. It has been well established that older adults have associative memory deficits and comparing them to young adults with a chronic history of mTBI was expected to provide insight into the possibility of parallel cognitive performance.

Moreover, a novel approach taken in this current thesis was to use the traditional paradigm for item and associative memory used by Naveh-Benjamin (2000) and expanding it to manipulate attentional resources. Constraining attentional resources may be the only way to detect group differences in the present paradigm. Forcing participants to dual task makes the task harder and puts strain on cognitive resources. The previous studies (e.g., Blanchet et al., 2009; Mangels et al., 2002) only showed differences between controls and mTBI when attentional resources were limited (divided at encoding), leading both authors to attribute differences to deficits in executive control. A divided attention paradigm might be more sensitive to cognitive issues in mTBI than if completed entirely under full attention.

In parallel, older adults and mTBI share neurological changes to the medial temporal lobe and prefrontal cortex, two areas whose functions are required to link or bind items to each other at encoding, and necessary to perform well on a test of associative memory (Allen & Fortin, 2013). Medial temporal lobe changes in mTBI are more generalized than older

adults (have been shown in atrophic white matter from axonal damage due to the lateral forces applied to the brain from an impact; Bigler, 2023), and this may influence whether any associative memory deficit is observable in an mTBI group. Creating a memory for an association is a more cognitively demanding task than for an item. Thus, if any similarity between older adults and young adults with mTBI were to emerge, it would be on a test of associative memory. Therefore, the primary goal in my thesis was to explore the possibility of an associative deficit in mTBI and document whether it interacts with availability of attentional resources.

The use of a cognitively demanding task also presents the opportunity to explore participants' ability to cope and changes in mental fatigue. As mentioned, a common complaint long after a TBI is lingering emotional control, poorer mental health, fatigue, and elevated levels of depression (see Belanger et al., 2005). However, standard neuropsychological tests are not designed to assess these, though they could be impacting cognitive task performance. In line with this suggestions, previous research has shown that both trait and state levels of fatigue are elevated in mTBI compared to controls (e.g., Berginström et al., 2018; Cantor et al., 2008; Möller et al., 2017). Ozen & Fernandes (2011) found that controls and mTBI performed similarly on a working memory task but that it took mTBI more time and cognitive resources to maintain performance. Thus, the implementation of a pre-post assessment of fatigue and affect allows for the possibility that behaviourally both groups are comparable, but differ on more subtle measures, like fatigue and affect that may be the etiological factors to the common everyday complaints made post-injury.

Chapter 2
Experiment 1: Examining Cognitive and Affective Impairment in Young Healthy, Young mTBI & Older Adults

2.1 Background & Hypothesis

We hypothesized that compared to healthy younger adults, older adults as well as young adults with *chronic* mTBI might share a common cognitive deficit in associative memory due to similar changes to the frontal and temporal lobes that may result in similar cognitive outcomes. We investigated differences in item and associative memory across the three groups (young adult controls, young adult mTBI, & older adults) using a recognition task that evaluates memory for single items and another for associated items. We hypothesized that compared to young adult controls, those with a history of mTBI would show a) impaired performance on the associative but not item memory tests and that b) this effect would be magnified when information is encoded under divided compared to full attention condition. The possibility that there could be a similar associative memory deficit in aging individuals and those with mTBI has yet to be fully investigated. Additionally, difficulties in completing cognitive tasks when attentional resources are limited (i.e., under divided attention) has also been suggested to be an explanation for the cognitive complaints made by mTBI individuals (Cicerone, 1996) Older adults have also shown deficits in completing cognitive tasks when attentional resources are limited, when compared to healthy younger adults (Anderson et al., 1998).

We further explored the impact of completing these demanding cognitive tasks on emotion regulation and fatigue, as both have been suggested to be affected in mTBI

individuals when completing such tasks (Berginstrom et al., 2018; Ozen & Fernandes, 2012; van der Horn et al., 2020). This assessment was done to try to quantify the frequently expressed complaints, in those with a remote mTBI, about their cognition. Moreover, to date no study has assessed fatigue, affect, and irritability levels in chronic mTBI participants, before and after a cognitively demanding task. This is important to consider as past work (Hellewell et al., 2020) showed that individuals with a chronic mTBI had over a three times higher risk of developing depression, even long after injury. Similarly, a review by Rao & Lyketsos (2000) suggests the most frequent symptoms post injury (6-24 months) were dysphoria, fatigue, irritability, and anhedonia, with approximately 25% experiencing major depressive episodes. This thesis sought to determine whether those with a remote mTBI showed baseline differences in these measures and whether these psychological effects were exacerbated following a challenging cognitive task. Moreover, mTBI is suggested to uniquely lead to emotional regulation difficulties compared to older adults, who instead demonstrate a positivity bias with advancing age (Carstensen & Mikels, 2005). Documenting these psychological effects would help validate the anecdotal claims by those with a remote mTBI of increased irritability, difficulty with emotional regulation, and fatigue, long after a brain injury.

2.2 Methods

2.2.1 Participants

Participants were recruited from two separate cohorts and placed into one of three groups: young adult (YA) control group, young adult with history of mTBI, and healthy older

adults (OA). The YA sample (aged 18-25) was recruited from SONA, a student research participation platform consisting of undergraduate University of Waterloo students currently enrolled in a psychology course. Participation in research studies is required for course fulfillment, or alternatively as bonus credit that can be used towards the course grade. Participants are required to complete a comprehensive pre-screen assessment that provides researchers information to determine inclusion and exclusion criteria.

The OA sample (aged 65+) was recruited through the Waterloo Research in Aging Participant Pool (WRAP), a database created through a community outreach program in the Waterloo Region that enlists healthy aging OAs aged 60+ to participate in research studies conducted at the University of Waterloo. Participants complete an intake interview with the WRAP coordinator, where they provide a complete personal and medical history. To be included in the database there must be no reported history of neurological or cognitive impairment. A WRAP coordinator develops lists of potential participants for researchers depending on their criteria requirements.

The study was conducted over a 12-month period between March 2022 and March 2023 and resulted in recruitment of a total of 113 participants. However, only data from 107 participants were included in statistical analysis. The remaining 6 participants were removed because of conflicting report of incidence of mTBI (n = 1), poor performance (n = 4) (corrected recognition score under full attention below 0), and difficulties understanding the task (n = 1). In total, 36 YA controls, 36 YA mTBI, and 35 OAs were included in the final sample. Demographic information and neuropsychological tests for each group, to better

characterize the sample, can be found in Table 1 and Table 2. Moreover, first language information can be found in Appendix C

Table 1

Experiment 1: Demographic characteristics of study sample

	Young Adult Controls		Young Adult mTBI		Older Adults	
	M	*SD*	*M*	*SD*	*M*	*SD*
Age	19.5	1.5	19.4	1.8	72.2	4.5
Years of Education	15.4	1.7	14.9	2.0	15.9	2.7
NAART Errors	27.5	10.3	25.4	8.9	16.2	9.0
MHV Score	17.6	3.7	20.2	3.4	24.5	3.5
MoCA Score	-	-	-	-	27.7	1.9
Number of mTBIs			1.9	0.9		

Note. NAART = North American Adult Reading Test. MHV = Mill Hill Vocabulary Scale. MoCA = Montreal Cognitive Assessment.

Table 2

Experiment 1: Demographic frequencies of study sample

Study Group	Handedness	Frequency	Percentage
YA Controls	Ambidextrous (Both)	2	5.56
	Left	4	11.11
	Right	30	83.33
	Total	36	
YA mTBI	Ambidextrous (Both)	0	0.00
	Left	8	22.22
	Right	28	77.78

Study Group	Handedness	Frequency	Percentage
	Total	36	
OA	Ambidextrous (Both)	0	0.00
	Left	4	11.43
	Right	31	88.57
	Total	35	
	Sex		
YA Controls	Female	23	63.89
	Male	13	36.11
	Total	36	
YA mTBI	Female	25	69.44
	Male	11	30.56
	Total	36	
OA	Female	27	77.14
	Male	8	22.86
	Total	35	
	Gender		
YA Controls	GQ/GNC/GNB/GF	2	5.56
	Man/Transman	13	36.11
	Woman/Transwoman	21	58.33
	Total	36	
YA mTBI	GQ/GNC/GNB/GF	0	0.00
	Man/Transman	11	30.56
	Woman/Transwoman	25	69.44
	Total	36	
OA	GQ/GNC/GNB/GF	0	0.00
	Man/Transman	8	22.86
	Woman/Transwoman	27	77.14
	Total	35	

Note. GQ/GNC/GNB/GF = Genderqueer/ Gender non-conforming/ Gender non-binary/ Gender fluid

2.2.2 Inclusion and Exclusion Criteria

A series of pre-screen questions were administered to the young adults (controls and mTBI). To be included in the study they were required to have been born in 1997 or later (to

maintain a cut-off age of 25 years old). Second, there were a sequence of questions pertaining to English language, where they had to endorse that they speak, read, and write English fluently. Additionally, the age at which they learned English had to be before 9. This age was selected to balance the need for English competency, as this could limit overall memory for English words in our study and having adequate participant numbers. The pre-screen questions related to English competency were included because the study examined memory for English words, which would be compromised if English competency were poor. During the study, participants also completed the Mill-Hill Vocabulary Scale (Raven, 1958), an additional indirect measure of English fluency with all participants exceeding the 30% grade cutoff. Additionally, to be eligible for the YA control group a participant had to indicate that they had never experienced a head injury before.

For the YA mTBI sample, the pre-screen questionnaire included questions on time since injury, post traumatic amnesia (PTA), and loss of consciousness (LOC). These questions were only made visible to participants who initially indicated having sustained a head injury in the past. Time since injury had to be greater than 3 months, but less than 3 years. This was to make certain that injuries were in the chronic stage of recovery without being too far removed, which could curtail potential deficits. PTA had to be self-declared as not occurring or to a maximum of 24 hours. LOC had to be self-declared as not occurring or to a maximum of 30 minutes. These requirements meet the ACRM (1993) diagnostic criteria for a mTBI. It must be noted that potential participants could also qualify if they indicated 'I do not know' for either the question pertaining to PTA or LOC. Additionally, it was possible for a participant to endorse not having LOC or PTA, which would not meet the ACRM

requirements of at least one being present for an mTBI. In total, four participants reported ‘I do not know’ when asked if they experienced PTA after their injury. These decisions were made due to the limited number of potential participants within the SONA database and the initial difficulties in recruitment when inclusion criteria were more conservative. The study was only made visible on SONA to those who met the inclusion and exclusion criteria requirements.

Finally, all potential participants were naïve to the true purpose of our study and were not made aware of the connection between the pre-screen concussion questions and the present study. This was done because of work done by Ozen & Fernandes (2010) who found a ‘diagnosis threat’ – when mTBI samples are made aware that they are being assessed because of their head injury history they conformed to their diagnosis and performed more poorly than if they were recruited blind.

For the OA sample much of the screening process was completed prior to their involvement in the present study. Participants were required to be born in 1957 and earlier to meet the accepted threshold of 65 years of age and older. Participants were also excluded if they indicated having had a head injury, hospitalization because of head injury, or loss of consciousness because of head injury. Additionally, participants confirmed they had no difficulties understanding conversation or reading ordinary print. Four participants were included who indicated they experienced a head injury early in life (i.e., adolescence, early adulthood). All older adult participants were given the Montral Cognitive Assessment (MoCA) at the completion of study to assess cognitive functioning. Participant scores ranged from 24-30, with a score of 25 or lower suggesting there may be mild cognitive impairment.

Six participants were recorded as having a score of 25 or lower. All participants were included in final analysis.

2.3 Measures

2.3.1 Stimuli

A total of 216 words were compiled from the database of words provided in Warriner et al. (2013). This database consists of 13,915 English words taken from three sources: Bradley and Lang's (1999) ANEW database, Van Overschelde et al's (2004) category norms, and the SUBTLEX-US Corpus (Brysbaert & New, 2009). The database included normative data on a 9-point scale of each word's valence (1 = unpleasant, 9= pleasant), arousal (1 = calm, 9= excited), and dominance (1 = controlled, 9 = in control). All words selected for this study were concrete nouns, between 4 to 7 letters in length (M = 5.48, SD = 0.99), had a neutral valence (M = 5.32, SD = 0.49), and were non-arousing (M = 3.80, SD = 0.74). See Appendix A for lists of words.

2.3.2 Mill-Hill Vocabulary Scale

The Mill-Hill Vocabulary Scale (Raven, 1958) was included to measure participants' verbal intelligence and familiarity with English words. Participants were given Set A of the scale, which consists of 44 words. The respondent's task is to select the correct synonym from a list of six alternatives provided. A final score of 14 or greater indicates a passing score for this scale. All participants included in this study achieved this threshold.

2.3.3 Concussion History Questionnaire

All participants completed a brief 5-item questionnaire on their traumatic brain injury (concussion) history (see Appendix B). Questions were asked about time since injury, LOC, PTA, number of previous TBIs, disorientation loss, and confusion.

2.3.4 Positive and Negative Affect Schedule

The 10-item International Positive and Negative Affect Schedule Short Form (I-PANAS-SF) developed by Thompson (2007) was used to measure participant affect during the study. The instrument has 10 terms split into two scales, with five terms (Hostile, Ashamed, Upset, Afraid, & Nervous) scored for negative affect and five terms (Active, Attentive, Alert, Determined, & Inspired) scored for positive affect. Each item is rated on a five-point Likert scale from *very slight or not at all* (1) to *extremely* (5). The final collective score ranges from 5-25 for each scale, with a higher score indicating a greater positive/negative affect.

2.3.5 Description of Feelings Questionnaire

Each participant completed a 3-item description of feelings questionnaire before and after study to assess levels of fatigue (see Appendix B). We created this questionnaire to assess state-level physical fatigue, cognitive fatigue, and irritability. Participants were asked to rate how much they agreed with the following statements, between 1 (strongly disagree) to 100 (strongly agree): 1) I currently feel physically fatigued, 2) I feel mentally drained right now, 3) I feel irritable at the moment. The order of questions was consistent for all participants.

2.3.6 National Adult Reading Test (North American Revision)

The National Adult Reading Test (North American Version) is a single word, oral reading test consisting of 61 items (Blair & Spreen, 1989). The words are all irregular, such that all words have an atypical phonemic pronunciation (e.g., "colonel"). As such, this makes the test an assessment of word vocabulary rather than their intelligence and knowledge of regular pronunciation norms. Participants are asked to read one word at a time from a list, while the experimenter scores them for correct pronunciation. The North American Version (referred to as NAART or NART-R) is an adaptation of the original National Adult Reading Test (NART) developed in the United Kingdom by Nelson & O'Connell (1978). The NAART substitutes many of the words from the NART to be more applicable to a North American sample. The number of pronunciation errors is recorded and entered in an equation to provide an estimate of their Verbal IQ (VIQ), Performance IQ (PIQ), and Full-Scale IQ (FSIQ) based on Wechsler Adult Intelligence Scale – Revised (Wechsler, 1981).

2.3.7 Montreal Cognitive Assessment

All older adult participants completed the Montreal Cognitive Assessment developed by Dr. Nasreddine in 1996 (Nasreddine et al., 2005). The assessment was developed as a clinical screening tool for detecting the presence of mild cognitive impairments (MCIs). It consists of seven sections that assess many cognitive domains including short-term memory, working memory, executive functioning, attention, visuospatial abilities, and language. Participants are scored between 0 and 30, with a score over 26 considered to indicate normal aging, while a score lower than 26 being indicative of the potential presence of mild cognitive impairment or dementia (Nasreddine et al., 2005). For the purposes of our study,

we did not use this assessment as a screening tool, but instead to characterize our older adult sample and to validate that our sample was indeed healthy aging.

2.4 Demographic Characteristics

. Independent samples *t*-test showed that YA mTBI had a significantly higher MHV score than YA controls, t (70) = 3.16, p = .002, d = 0.746. Moreover, OAs had significantly higher MHV than YA controls, t (69) = 8.30, p < .001, d = 1.97, and YA mTBI, t (69) = 5.37, p < .001, d = 1.27. These findings are inline with previous research demonstrating that age is a determinant of success on a vocabulary test, with older adults outperforming their young adult counterparts on average (Ben-David et al., 2015; Verhaeghen, 2003). OAs also scored fewer NAART errors than both YA controls, t (69) = 4.92, p < .001, d = 1.17, and YA mTBI, t (69) = 4.94, p < .001, d = 1.17. YA controls and YA mTBI did not differ on the NAART (p = .60). All three groups were comparable on years of education (p > .35).

2.4.1 Clinical TBI Characteristics

TBI history was taken from the concussion history questionnaire completed by all participants. However, self-reported symptomology differed between pre-screen reporting and the second assessment in lab. Data were tabulated from the second assessment completed in the lab. Within the mTBI group the average number of TBIs was 1.94 (SD = 0.92), and ranged from one (n = 15), two (n = 9), three (n = 11), and four (n = 1) separate self-declared incidents of a TBI. Participants were instructed to report symptomology for only their most recent TBI; thus, we are naïve to their extended injury history. Time since injury ranged from less than 3 months ago (n = 2), 4-12 months ago (n = 6), 1 year ago (n = 5), 2 years ago (n =

7), 3 years ago (*n* = 8), and over 3 years ago (*n* = 8). The participants who indicated having an injury less than 3 months ago and more than 3 years ago were included because they met the criteria initially in the first assessment during the pre-screen (chronic stage, 3 months to 3 years). LOC was reported in 10 cases: 1-59 seconds (*n* = 8), 1-5 minutes (*n* = 1), greater than 30 minutes (*n* = 1). PTA was reported in 10 cases: 1-59 seconds (*n* = 6), 1-60 minutes (*n* = 2), 1-24 hours (*n* = 1), while three participants declared not knowing. In total, 21 participants reported having no LOC *and* no PTA, while 4 participants reported having *both* LOC and PTA.

2.4.2 Additional Mass Testing Sample Characteristics

A portion of our sample completed the SONA mass testing questionnaire independently from our study (YA Controls = 25, YA mTBI = 26). Access was granted to their answers following the completion of the current study. The purpose here was to compare the young adult groups on trait level measures of attention, mood, and fatigue. We looked at participants scores on the Attention-Related Cognitive Errors Scale (ARCES; Cheyne et al., 2006), the 21-item Depression, Anxiety, and Stress Scale (DASS-21; Loviband & Loviband, 1995; Henry & Crawford, 2005), and the 16-item Difficulties in Emotion Regulation Scale (DERS-16; Bjureberg et al., 2015; Gratz & Roemer, 2004). These measures were only gathered in the YA groups and groups were compared.

2.4.2.1 ARCES

The Attention-Related Cognitive Errors Scale (ARCES) is a scale that assess everyday mistakes that occur from lapses in attention. Scores are summated and range from

12-60, with higher scores indicating greater lapses in attention daily. An independent samples *t*-test was conducted to compare the young (*M* = 36.32, *SD* = 8.00) and YA mTBI (*M* = 41.19, *SD* = 8.24). There was a significant difference between groups, such that the YA mTBI scored higher on the ARCES than YA controls, *t* (49) = 2.14, *p* = .037, *d* = .60.

2.4.2.2 DASS

The 21-item Depression, Anxiety, and Stress Scale (DASS-21) is a set of three separate subscales of seven items with scores for each scale ranging from 0 (low psychological distress) to 21 (high psychological distress The grand scale contains subscales measuring depression (YA controls: *M* = 11.28, *SD* = 11.70, YA mTBI: *M* = 9.62, *SD* = 9.65), anxiety (YA controls: *M* = 6.32, *SD* = 5.68, YA mTBI: *M* = 8.58, *SD* = 6.82), and stress (YA controls: *M* = 12.64, *SD* = 10.89, YA mTBI: *M* = 10.62, *SD* = 7.51) over the past week.. Independent samples *t*-test found no significant difference between groups on each subscale (*p* > .05).

2.4.2.3 DERS

The 16-item Difficulties in Emotion Regulation Scale (DERS-16) is a self-report measure of an individual's difficulties levels of emotion regulation. Scores range from 16-80, with higher scores indicating greater difficulty. Independent samples *t*-test found no significant difference between YA controls (*M* = 43.28, *SD* = 13.95) and YA mTBI (*M* = 44.15, *SD* = 17.15) (*p* > .05).

2.5 Procedure

Participants were assessed individually in a small testing room with the experimenter present throughout. Sessions were scheduled to last 1 hour, with variation in length due to individual differences in speed of completing tasks. Participants were seated in front of a 24-inch computer monitor. Stimulus display and response recording for the memory test were accomplished using E-Prime 3.0 Software (Psychology Software Tools, Pittsburgh, PA).

The word lists presented to participants were taken from a larger set of selected words and were shown to all.; From the larger set, 160 words were randomly placed into word-pairs to create two study lists of 40 word-pairs. The lists were matched for word length, valence, arousal, and dominance (the extent to which a word denotes something that is weak/submissive or strong/dominant, see Warriner et al., 2013, p. 1192) ($p > .05$). See Table 3 for breakdown of each list. Forty additional words were selected to serve as foils during the item memory test, 20 for List I and 20 for List II. Again, these foil lists were matched for word length, valence, arousal, dominance with one another and with the primary word-pair lists ($p > .05$). The remaining 16 words were used to create buffers in the list, such that two-buffer word-pairs were placed at the beginning and end of List I and List II to reduce any primacy or recency effects.

Table 3

Characteristics of word lists in Experiments 1 and 2

Word List	Word Length	Valence	Arousal	Dominance
List I	5.61 (0.67)	5.29 (0.31)	3.78 (0.47)	5.49 (0.39)

List II	5.44 (0.52)	5.32 (0.35)	3.84 (0.35)	5.45 (0.39)
Foil List I	5.20 (1.15)	5.26 (0.52)	3.61 (0.83)	5.31 (0.61)
Foil List II	5.35 (1.04)	5.48 (0.40)	3.91 (0.83)	5.44 (0.56)

Note. Standard deviation is presented in parentheses.

After obtaining informed consent, the participant completed both the Description of Feelings Questionnaire and the I-PANAS-SF (Thompson, 2007), to evaluate their baseline fatigue levels and emotional state. Next, participants were guided by the experimenter through a slideshow presentation through Microsoft PowerPoint (detailing the study instructions and memory tasks. Participants were then guided through a practice version of the encoding and retrieval phases. During the practice phase of encoding, participants were shown two word-pairs at a time presented centrally on screen in size 32 *Century Gothic* font. In the practice phase encoding was not timed, and word-pairs remained on screen until the participant clicked, this was done to coordinate experimenter instructions with visual presentation.

Following this, participants completed a practice Item recognition and practice Associative recognition test. In the practice item recognition test participants were shown one word at a time and were instructed to either indicate if the word was OLD (shown in the original list) or NEW (never shown in the original list) by pressing the Z key for OLD and the C key for NEW on their keyboard. In the Associative recognition memory test (always completed after the item recognition test), they were shown word-pairs and were instructed to indicate if the pair of words was OLD (intact word-pair shown in the original list) or NEW

(rearranged words from the original list that were not presented together). Again, participants were told to press the Z key to indicate an OLD response and the C key to indicate a NEW response. There was no time limit to respond, though participants were asked to make decisions as quickly and accurately as possible. Throughout the presentation the experimenter guided the participants through the correct response for each simulated test item.

Participants were then introduced to the attention manipulation and were instructed that while learning one of the lists they would have to multi-task by simultaneously completing a digit-monitoring task. The digit-monitoring task consisted of auditory presentation of a continuous string of numbers between 10-99, every 2 seconds, in a pseudo-random order. Participants were told to say "Yes" every time they heard three odd numbers spoken in a row. Each correct identification was recorded manually on a sheet of paper by the experimenter. A baseline measure of digit task performance was completed before advancing to the experimental phase. The duration of this task was half the length of what they would be presented during the study and consisted of 5 distinct three-odd number sequences embedded within a string of 33 numbers. Additionally, the string contained two 2-odd number lures, two 1-odd number lures, and 12 even numbers.

Next participants completed the experimental phase. Participants were told they would repeat the same procedures as in practice, but with longer lists. Each participant completed two study-test cycles, one under full attention (in both the encoding and retrieval phase) and the next under divided attention in which the encoding phase was completed concurrently with the digit-monitoring task and the retrieval phase was under full attention.

List I was used in the full attention condition, while List II was used in the divided attention condition, and the order of presentation of conditions was the same for all participants.

During encoding in the experimental phase, each pair had a dash between them and was centrally presented on the screen in size 24 *Consolas* font. Pairs were presented sequentially, one at a time, in random order, for 3 seconds each. In both attention conditions, participants were told to study in preparation for an item and an associative recognition test.

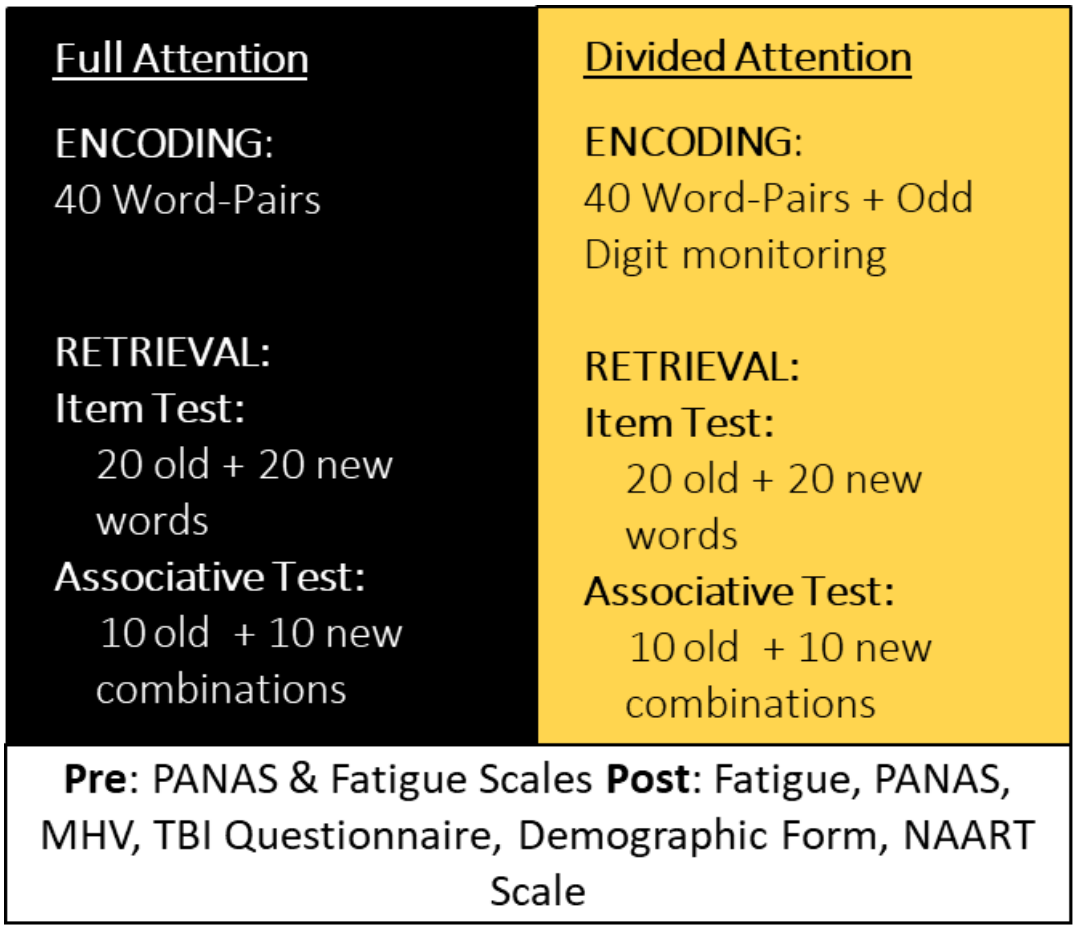
During the encoding phase for each condition, 80 words (40 word-pairs) were presented using the same font and duration as in the practice phase. The encoding phase thus took 2 minutes and 12 seconds for each condition. Following each of the encoding phases, participants then immediately completed both an item and associative recognition tests, in that order. In the item recognition test, a total of 40 words were shown, 20 of which were previously seen in the encoding phase and 20 were foils that were never shown. For the Item recognition test words were presented centrally in *Consolas* font 24 point in random order with a 500 msec blank page in between each trial. As were instructed in the practice phase, participants pressed the corresponding key to indicate whether they recognized the word shown on each trial as being from the encoding phase.

Following this, participants completed the associative recognition test in which 20 word-pairs were shown, 10 of which were intact pairs from the encoding phase, and 10 of which were rearranged pairs, presented in the encoding phase but paired with a different word. Font properties and duration were the same as in the Item recognition test. For both the Item and Associative tests, participants were given unlimited time to make their keypress responses. No words were repeated between the two tests.

In the divided attention condition, the encoding and recognition test procedure was near identical. The only difference was that during encoding participants had to concurrently perform the digit-monitoring task, while being presented with List II word pairs. (See Figure 1 for visual representation of procedure). The audio track consisted of 10 distinct three-odd number sequences that the participant was to identify within a 66 number string. The string followed the same format and timing as the practice phase.

Figure 1

Diagram of experimental procedure



2.6 Results

2.6.1 Memory Data

All statistics were conducted comparing performance across the 3 groups (YA controls, YA mTBI, and OA). We also conducted analyses comparing performance in just the YA and YA mTBI groups (see Appendix D). All statistical analyses were conducted using JASP (Version 0.17.1; Department of Psychological Methods, University of Amsterdam).

2.6.1.1 Data Normalization

Data were normalized with 90% Winsorization for all groups (see Dixon & Yuen, 1974 for review of Winsorizing). This was done for all experimental data: accuracy, RT, and emotion scales to control for the variability, and subsequent outliers, which were found in each measure (i.e., memory, reaction time, affective measures). The process smooths and normalizes the distribution and prevents extreme scores from erroneously influencing the data, while maintaining the shape of the distribution. Briefly, a 90% Winsorization is when each value on a given measure that exceeds the 95^{th} percentile is transformed and set at the 95^{th} percentile value. Alternatively, any measured value that falls below the 5^{th} percentile is transformed and set to the 5^{th} percentile. For our study, all outlier and percentile calculations were done within each group and measure to mitigate any influence of group differences masking possible outliers. This procedure was adopted to account for the inherent variability that comes with assessments of those with mTBI (Rosenbaum & Lipton, 2012).

2.6.1.2 Corrected Recognition

Corrected recognition was used to assess memory performance. Corrected recognition was tabulated as the number of correct endorsements of 'old' words (on Item test) or word pairs (on Associative test) minus the number of incorrect endorsements of 'new' words or word pairs as 'old.' For the item test, 20 new words and 20 old words were shown, therefore Hit rate and False alarm rate were calculated by taking their corresponding scores and dividing them by 20.

For the associative test, 10 original combinations and 10 rearranged combinations were shown. Hit rate and false alarm rates were calculated by taking their corresponding scores and dividing them by 10. See Table 4 for the hit rate, false alarm rate, and corrected recognition of each group, with each variable being independently winsorized for data normalization.

Table 4

Experiment 1: Recognition Scores on Memory Tests by Attention

Test Type	Attention	Study Group	HR	FA	CR
Item	Full	YA Control	0.77 (0.14)	0.20 (0.14)	0.58 (0.19)
		YA mTBI	0.75 (0.14)	0.21 (0.12)	0.53 (0.16)
		OA	0.74 (0.16)	0.19 (0.14)	0.54 (0.15)
	Divided	YA Control	0.61 (0.15)	0.32 (0.17)	0.28 (0.16)
		YA mTBI	0.61 (0.15)	0.36 (0.13)	0.25 (0.17)
		OA	0.58 (0.16)	0.35 (0.19)	0.23 (0.16)
Associative	Full	YA Control	0.60 (0.18)	0.27 (0.18)	0.33 (0.24)
		YA mTBI	0.63 (0.18)	0.24 (0.16)	0.39 (0.24)
		OA	0.60 (0.24)	0.40 (0.22)	0.20 (0.28)
	Divided	YA Control	0.51 (0.22)	0.29 (0.17)	0.22 (0.25)
		YA mTBI	0.46 (0.17)	0.31 (0.18)	0.15 (0.18)
		OA	0.46 (0.25)	0.38 (0.26)	0.08 (0.16)

Note. Standard deviation is presented in parentheses. CR = Corrected Recognition. HR = Hit Rate. FA = False Alarm Rate. YA = Young Adult. OA = Older Adult

2.6.2 Recognition Performance

To examine differences in recognition performance, a 2 x 2 x 3 mixed model ANOVA was completed. Corrected recognition (hit rate – false alarm rate) scores were the dependent variable. The repeated measure factors were Attention (full, divided) and Test type (item, associative) and the between-subject factor was Group (YA control, YA mTBI, and OA). There was a significant main effect of Test Type, F (1, 104) = 132.208, $p < .001$, $\eta_p^2 = .560$, such that recognition performance was greater on the item than associative memory test. Additionally, there was a significant main effect of Attention, F (1, 104) = 158.134, $p < .001$, $\eta_p^2 = .603$, such that recognition memory was greater under full attention compared to divided attention. Thus, when attention was divided there was a cost to memory performance. Additionally, there was a main effect of Group, F (2, 104) = 4.481, $p = .014$, $\eta_p^2 = .079$. Bonferroni post-hoc testing showed that the OA group had significantly poorer overall memory compared to YA controls ($t = 2.871$, $p_{bonf} = .015$, $d = .450$) but not the YA mTBI group ($t = 2.187$, $p_{bonf} = .093$, $d = 0.343$). The YA groups did not significantly differ ($t = 0.690$, $p_{bonf} = 1$, $d = 0.107$).

There was also a significant Test Type x Group interaction, F (2, 104) = 5.785, $p = .004$, $\eta_p^2 = .100$. Simple main effect analysis showed that Test Type had a significant effect for all three groups ($p < .001$). Follow up Bonferroni post-hoc testing showed that the interaction was driven by OA Associative memory performance significantly differing from both YA controls ($p_{bonf} = .005$) and YA mTBI ($p_{bonf} = .006$) (see Figure 2), but no differences

were found for item memory across all three groups (p_{bonf} = 1) (see Figure 3). There was also a significant interaction between Test Type x Attention, F (1, 104) = 17.736, p < .001, η_p^2 = .146. Bonferroni post-hoc testing showed that all pairwise comparisons were significant (p_{bonf} < .001) except divided item memory and full attention associative memory (p_{bonf} = .214). No significant three-way interaction between Attention x Test Type x Group was found (p > .05).

Figure 2

Experiment 1: Associative test memory performance between Group

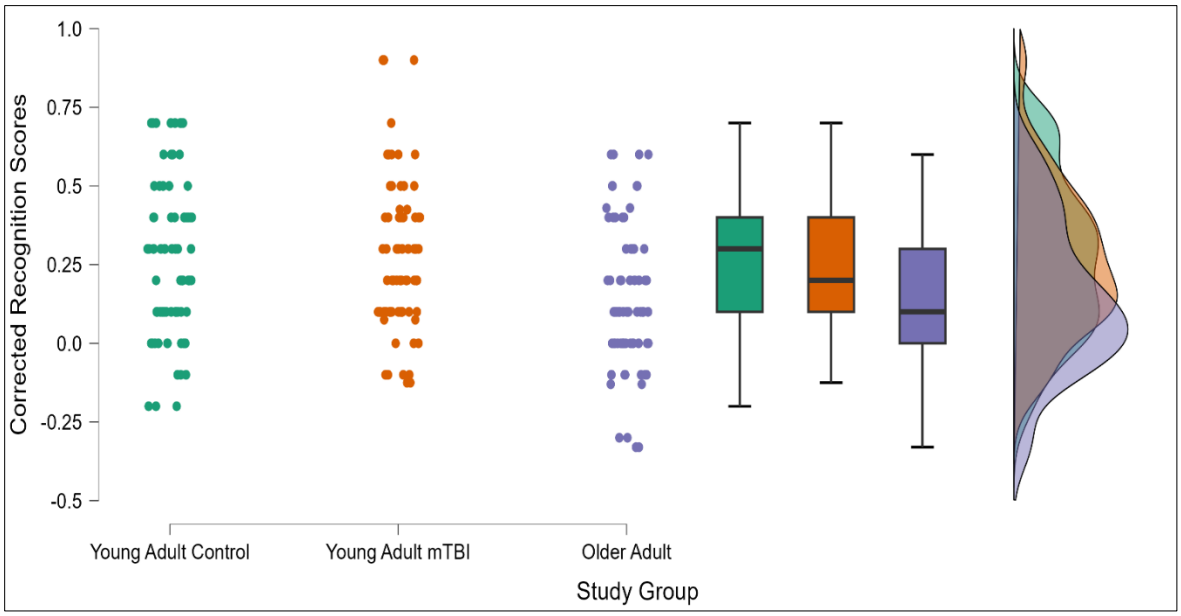
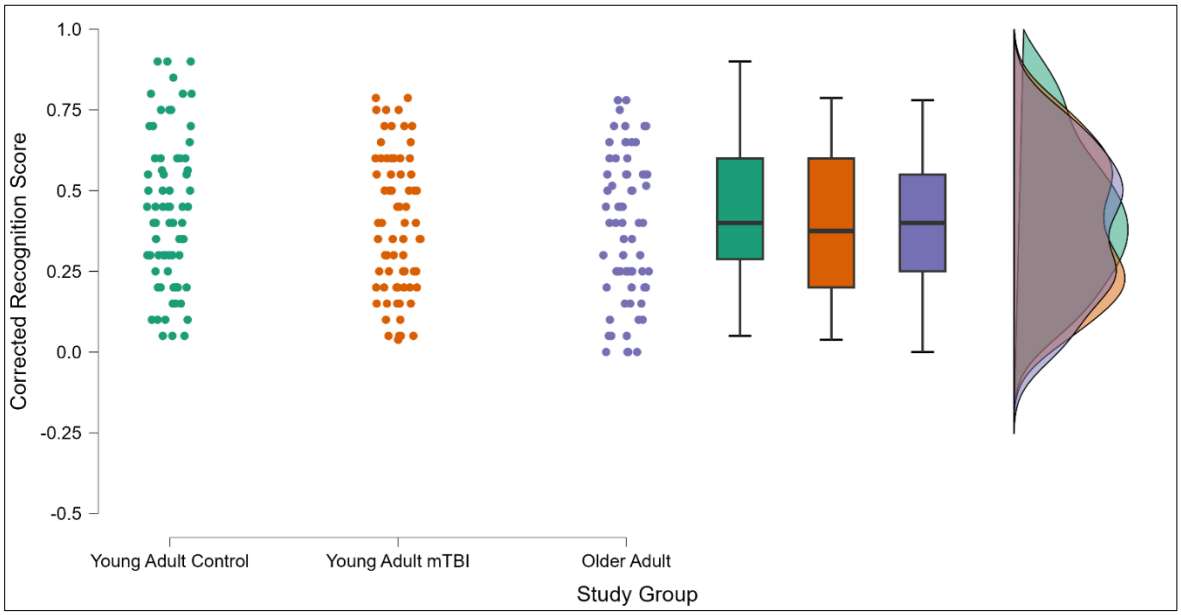


Figure 3

Experiment 1: Item test memory performance between Group



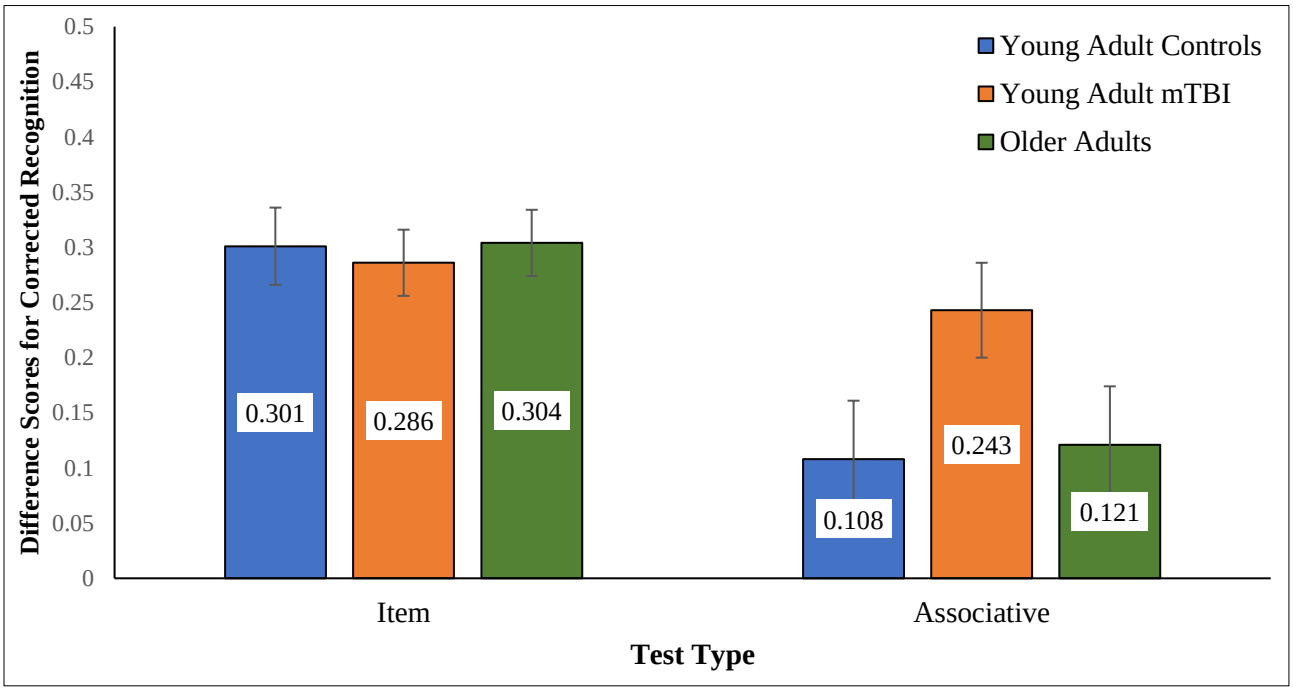
2.6.3 Difference Scores

A critical a priori comparison was to look at difference scores between groups based on the findings of previous studies (i.e., Blanchet et al., 2009, Mangels et al., 2002). Difference scores in memory performance were calculated by subtracting corrected recognition scores in the Divided Attention from the Full attention condition. Additionally, this calculation was done for each Test Type condition (Item & Associative). Proportional difference scores were unable to be calculated because of issues with dividing by zero, therefore, we used raw difference scores. Based on a-priori predictions of differences between Study Group based on Attention, independent samples *t*-tests were conducted comparing the Groups on Item and Associative tests. YA mTBI showed a significantly greater drop in corrected recognition performance (i.e., larger difference scores) compared to YA controls on the Associative test when comparing their Full Attention scores to their

Divided Attention scores, t (70) = 1.96, p = .05, d = 0.46 (see Figure 4). Difference scores did not reach significance between YA mTBI and OA (p = 0.08).

Figure 4

Experiment 1: Difference memory scores between Group for each Test Type



Note. Error bars represent +/- 1 SE.

2.6.4 Response Time

Response times to make keypress responses to correct items were analyzed in a 2 x 2 x 3 repeated measures ANOVA with the within-factors being Attention (Full & Divided) and Test Type (Item & Associative), while the between-factor was Group (YA controls, YA mTBI, and OA). The dependent variable was median response time for correct memory test responses. Thus, if a participant did not have one correct response for each condition, they were excluded from analysis. One YA control and three OAs were removed from analysis,

resulting in the exclusion of 3.7% of all participants data. There was a significant main effect of Attention, F (1,100) = 8.015, p = .006, η_p^2 = .074, due to longer RTs for divided than full attention condition, and a main effect of Test Type, F (1,100) = 224.471, p < .001, η_p^2 = .692, due to longer RTs for associative than Item conditions. Additionally, there was a main effect of Group, F (2,100) = 5.215, p = .007, η_p^2 = .094. Bonferroni post-hoc testing found that OA showed significantly slower response times compared to both YA controls (p_{bonf} = 0.011) and YA mTBI (p_{bonf} = 0.029). No other significant comparisons were present. See Table 5 for Response Time performance.

Table 5

Median response time for correct memory test responses (in milliseconds)

Test Type	Attention	Study Group	N	Mean
Item	Full	YA Control	35	887.81 (289.14)
		YA mTBI	36	953.93 (193.85)
		OA	32	1143.54 (289.14)
	Divided	YA Control	35	1072.86 (381.71)
		YA mTBI	36	1161.33 (485.48)
		OA	32	1280.10 (342.44)
Associative	Full	YA Control	35	1718.70 (670.90)
		YA mTBI	36	1744.37 (722.38)
		OA	32	2036.97 (689.65)
	Divided	YA Control	35	1836.01 (955.36)
		YA mTBI	36	1797.09 (596.10)
		OA	32	2228.11 (931.07)

Note. Standard deviation is presented in parentheses. 90% Winsorized transformation of data within-group.

2.6.5 Distractor Task

A 2 x 3 repeated measures ANOVA was conducted to assess performance on the odd-digit monitoring distractor task. The hit rate for making correct endorsements of a sequence

of odd numbers was the dependent variable. The repeated measure factor was Condition (baseline, dual-task) and the between-subject factor was Group (YA control, YA mTBI, and OA). There was a main effect of Condition, F (1,104) = 17.949, $p < .001$, $\eta_p^2 = .147$, such that, as expected, digit hit rate in the baseline condition was greater than during the dual-task condition. Moreover, there was a significant main effect of Group, F (2,104) = 5.931, $p = .004$, $\eta_p^2 = .102$. Bonferroni post-hoc testing found that the OA group had a significantly lower digit hit rates compared to the YA controls ($p_{bonf} = .003$), but not compared to YA mTBI ($p_{bonf} = 0.108$). Finally, there was a significant Condition x Group interaction, F (2,104) = 3.494, $p = .034$, $\eta_p^2 = .063$. Bonferroni post-hoc testing revealed that, in the OA group, digit hit rate during the dual-task condition was significantly lower than for YA Controls ($p_{bonf} < .001$), but not than YA mTBI ($p_{bonf} = .062$). Moreover, the hit rate in the OA group during baseline was significantly higher than during study ($p_{bonf} < .001$). No other significant differences emerged. See Table 6 for odd-digit monitoring performance across all groups.

Table 6

Experiment 1: Odd-digit monitoring distractor task hit rate performance

Study Group	Baseline Hit Rate	Dual task Hit Rate
YA Control	0.95 (0.15)	0.91 (0.11)
YA mTBI	0.92 (0.20)	0.84 (0.21)
OA	0.90 (0.21)	0.69 (0.32)

Note. Standard deviation is presented in parentheses.

Difference scores between baseline and dual-task conditions were calculated. Correlations were run in each group independently to assess whether digit performance scores and corrected recognition scores for item and associative memory were related. No significant correlations were found ($p > .05$).

2.6.6 Affective Measures

Affective measures were taken pre and post study using the Description of Feelings questionnaire and PANAS (See Table 7)

Table 7

Experiment 1: Self-reported ratings of fatigue and affect pre- and post-experiment

Measurement	Time	Study Group	Mean
Physical Fatigue	Pre-Experiment	YA Controls	36.60 (24.62)
		YA mTBI	41.61 (23.80)
		OA	20.87 (21.71)
	Post-Experiment	YA Controls	32.00 (24.19)
		YA mTBI	38.06 (20.51)
		OA	22.24 (19.85)
Mental Fatigue	Pre-Experiment	YA Controls	38.39 (30.59)
		YA mTBI	48.13 (26.89)
		OA	14.26 (19.95)
	Post-Experiment	YA Controls	38.78 (29.27)
		YA mTBI	51.29 (22.76)
		OA	30.31 (23.91)
Irritability	Pre-Experiment	YA Controls	9.14 (11.49)
		YA mTBI	8.39 (9.35)
		OA	3.85 (4.40)
	Post-Experiment	YA Controls	8.03 (8.64)
		YA mTBI	9.67 (9.97)
		OA	11.63 (14.55)
Total Fatigue	Pre-Experiment	YA Controls	85.86 (61.26)
		YA mTBI	97.53 (46.52)
		OA	39.81 (41.54)
	Post-Experiment	YA Controls	78.94 (55.09)
		YA mTBI	101.00 (38.99)

		OA	64.72 (46.57)
Positive Affect (PANAS)	Pre-Experiment	YA Controls	16.78 (2.75)
		YA mTBI	16.31 (2.79)
		OA	17.03 (3.87)
	Post-Experiment	YA Controls	15.81 (2.99)
		YA mTBI	15.75 (3.81)
		OA	15.83 (4.13)
Negative Affect (PANAS)	Pre-Experiment	YA Controls	9.69 (2.90)
		YA mTBI	9.61 (3.26)
		OA	6.40 (1.82)
	Post-Experiment	YA Controls	9.33 (3.22)
		YA mTBI	10.06 (3.63)
		OA	7.00 (1.68)

Note. Standard deviations are in parentheses. Physical fatigue, mental fatigue, irritability, and total score have 90% winsorized transformation within-group.

2.6.6.1 Fatigue

Fatigue measures were calculated using the Description of Feelings Questionnaire, which provided a pre and post score of physical and mental fatigue, irritability, and a total score of the three items combined. Four separate repeated-measures ANOVAs were run for each item, with the within-subject factor being Time (Pre & Post) and the between-subject factor being Group (YA controls, YA mTBI, and OAs). It must be noted that OAs reported lower scores for each of the items within the questionnaire. This is because of the tendency for OAs in our study to report more conservatively on self-report measures rather than a true reflection of being less fatigued.

For physical fatigue, there was no main effect of Time ($p = .151$). However, there was a main effect of Group, F (2, 104) = 7.022, $p = .001$, $\eta_p^2 = .105$. Bonferroni post-hoc testing showed that the OA group reported lower levels of physical fatigue than YA Controls (p_{bonf} =

.037), and YA mTBI (p_{bonf} = .001). YA controls and YA mTBI did not differ (p_{bonf} = .801). No significant interactions were found.

For mental fatigue, there was a main effect of Time, F (1, 104) = 10.778, p = .001, η_p^2 = .094, such that mental fatigue scores were higher post study than pre study. There was also a main effect of Group, F (2, 104) = 11.98, p < .001, η_p^2 = .187. Bonferroni post-hoc testing showed that the OA group reported lower levels of mental fatigue than YA Controls (p_{bonf} = .014), and YA mTBI (p_{bonf} < .001). YA controls and YA mTBI did not differ (p_{bonf} = .148). Finally, there was a significant Time x Group interaction, F (2, 104) = 5.822, p = .004, η_p^2 = .101. Simple main effect analyses showed that for OAs, the effect of Time (pre to post) led to an increase in mental fatigue, F (1,35) = 21.503, p < .001. This effect was not found in YA controls (p = 0.918) or YA mTBI (p = 0.316).

For irritability, there was a main effect of Time, F (1, 104) = 6.606, p = .012, η_p^2 = .060, such that irritability scores were higher post study than pre study. There was no main effect of Group (p = 0.819). There was a significant interaction of Time x Group, F (2, 104) = 6.591, p = .002, η_p^2 = .112. Simple main effect analyses showed that for OAs, the effect of time (pre to post) led to an increase in irritability, F (1,35) = 10.520, p = .003. This effect was not found in YA controls (p = 0.383) or YA mTBI (p = 0.412).

For total fatigue, the main effect of Time approached significance, F (1, 104) = 3.540, p = .063, η_p^2 = .033, such that total fatigue scores increased post study. There was a main effect of Group, F (2, 104) = 9.978, p < .001, η_p^2 = .161. Bonferroni post-hoc testing showed that the OA group reported lower levels of total fatigue than YA Controls (p_{bonf} = .017), and YA mTBI (p_{bonf} < .001). YA controls and YA mTBI did not differ (p_{bonf} = .341). Finally,

there was a significant interaction of Time x Group, F (2, 104) = 6.031, p = .003, η_p^2 = .104. Simple main effect analysis showed that for OAs, the effect of Time (pre to post) led to an increase in total fatigue scores, F (1, 35) = 12.206, p = .001. This effect was not found in YA controls (p = 0.354) or YA mTBI (p = 0.494).

2.6.6.2 Correlations

Correlational analyses were run within-group for a priori predictions of group differences on fatigue to assess ability to cope with demanding cognitive tasks. We compared proportional percent changes in fatigue items with each corrected recognition scores for each memory test. Proportional changes were calculated by subtracting each participant's post-study score from their pre-study score and then dividing the difference by their pre-study score, to get a proportion of change. This value was then multiplied by 100 to get a percent change. Pearson R correlational analyses were run independently for each group.

There were no significant correlations found between proportional change in physical fatigue or irritability and corrected recognition scores. In YA Controls, there was a significant correlation between proportional change in mental fatigue, r (36) = .39, p = .018, and total fatigue, r (36) = .37, p = .027 with corrected recognition scores on the full attention associative test. For the YA mTBI group there was a significant correlation between proportional change in mental fatigue r (36) = -.34, p = .046, and total fatigue, r (36) = -.349, p = .037, with corrected recognition scores on the divided attention item test. Additionally, there was a significant correlation with proportional change of total fatigue and corrected recognition scores on the divided attention associative test, r (36) = -.36, p = .033. The

correlation between proportional change in mental fatigue and corrected recognition scores on the divided attention associative test was significant, r (36) = -.32, p = .05. Finally, in the OA sample there were no significant correlations. See Figures 5-7 for correlation plots of proportional change in mental fatigue and corrected recognition scores on the divided attention associative memory test.

Figure 5

Young Adult Controls: Proportional Change in Mental Fatigue and Corrected Recognition Scores for the Divided Attention Associative Memory Test

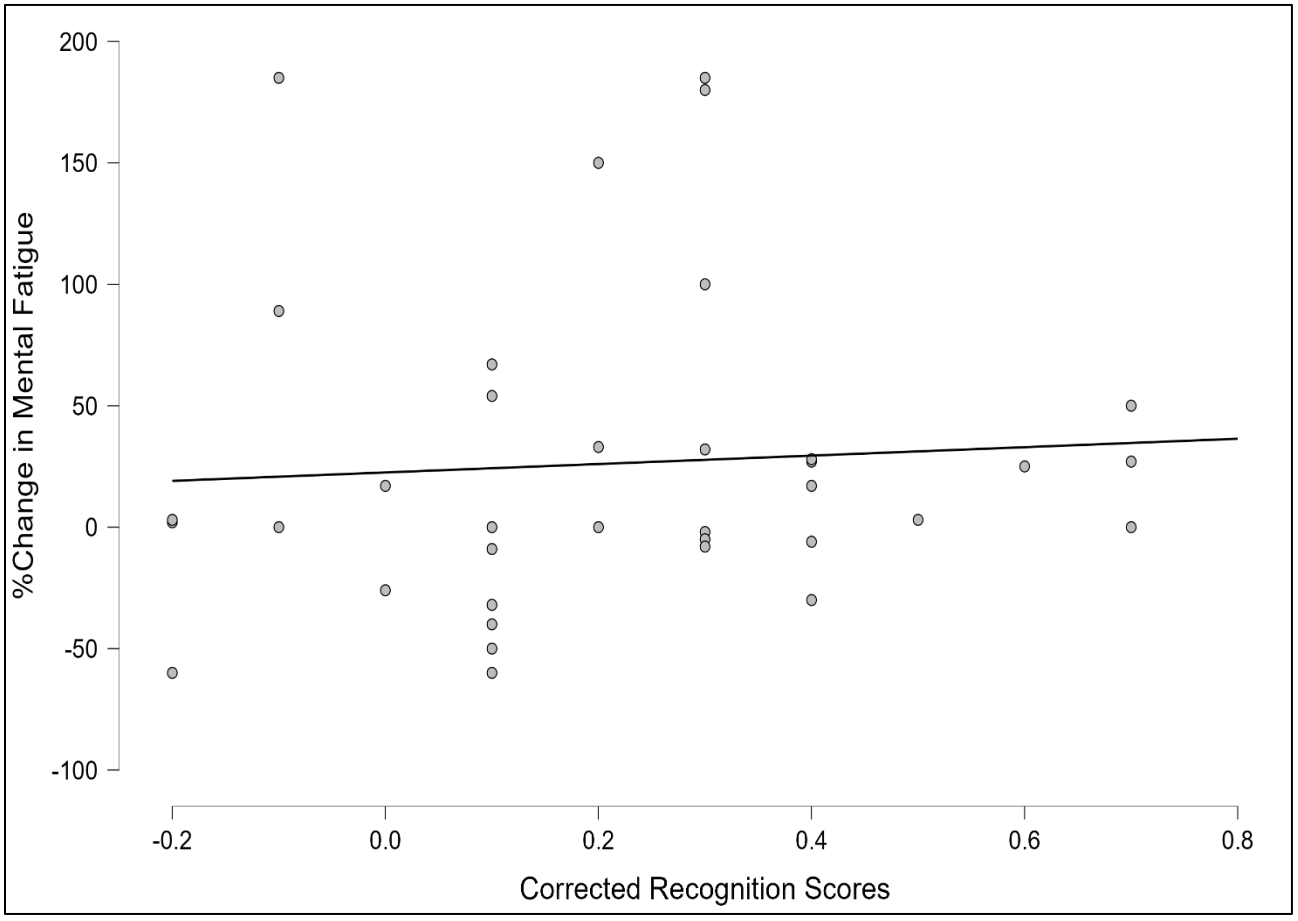


Figure 6

Young Adult mTBIs: Proportional Change in Mental Fatigue and Corrected Recognition Scores for the Divided Attention Associative Memory Test

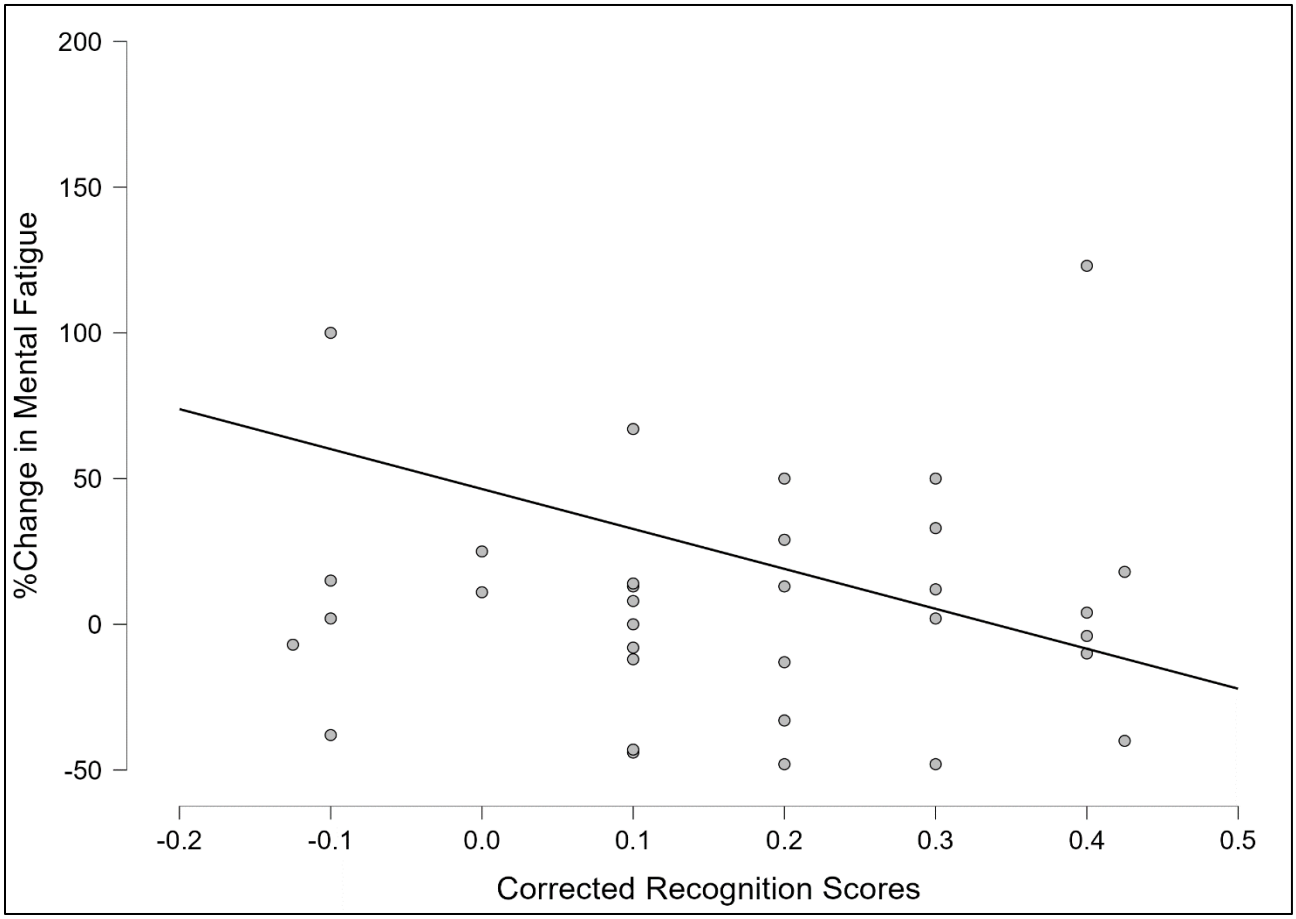
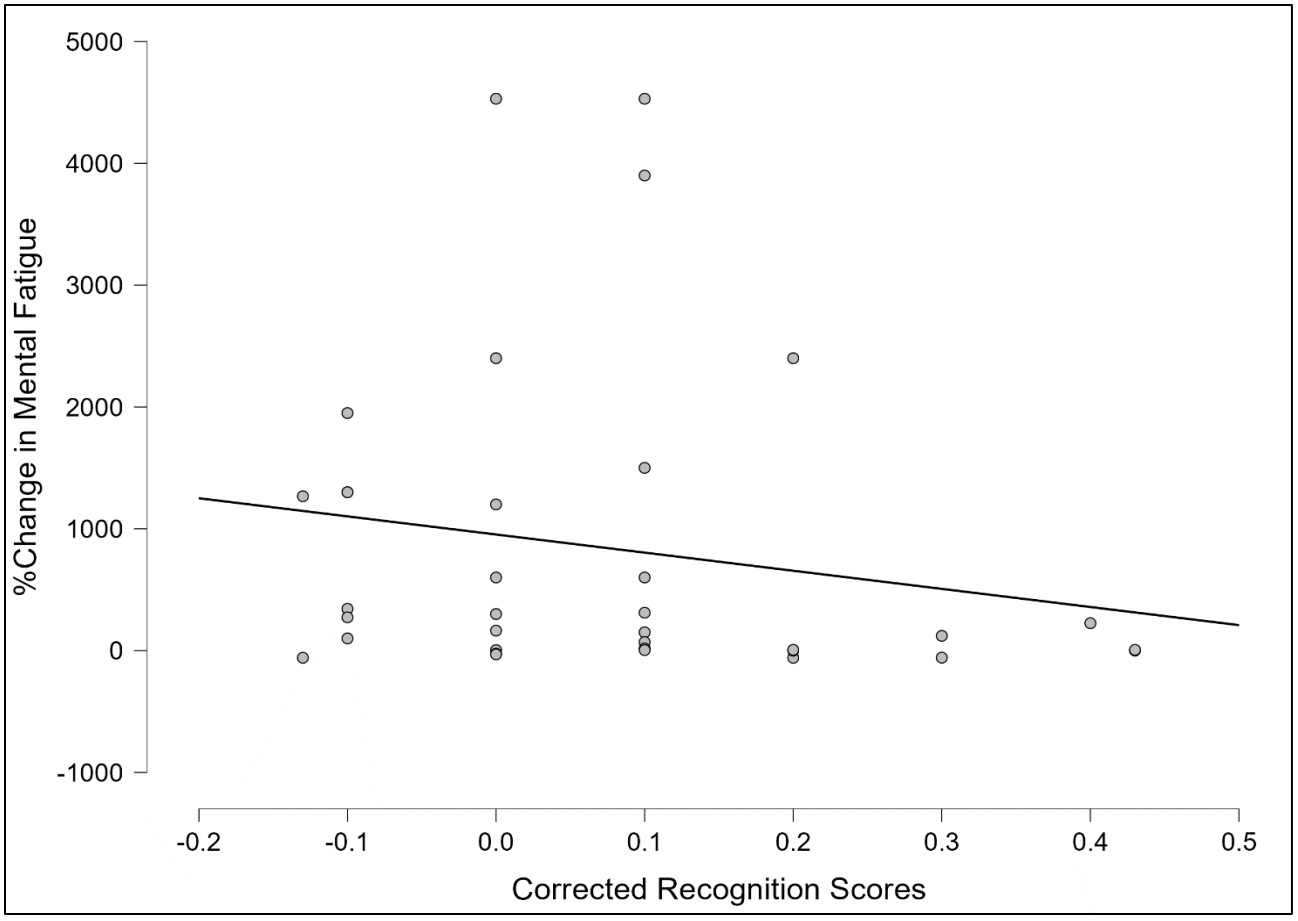


Figure 7

Older Adults: Proportional Change in Mental Fatigue and Corrected Recognition Scores for the Divided Attention Associative Memory Test



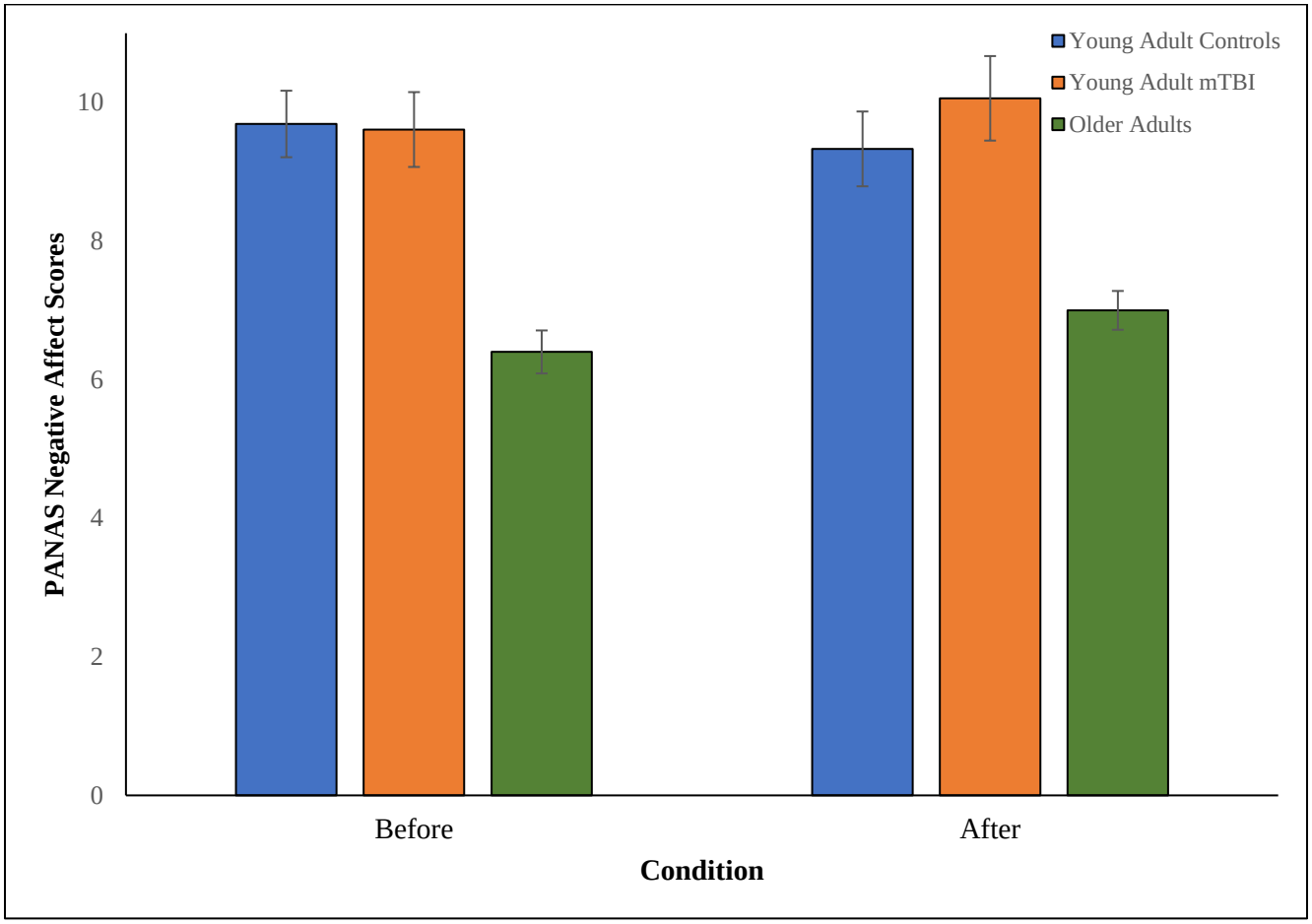
2.6.6.3 Mood

Independent ratings of positive and negative affect scores on the PANAS rated before and again after the experiment were tabulated. A higher score on the positive subscale indicates a more positive affect and a higher score on the negative subscale indicates a more negative affect. Two separate 2 x 3 mixed model ANOVAs were conducted, one for positive affect and one for negative affect scores, with the within-factor being Time (Before and After the study), and the between factor being Group (YA Controls, YA mTBI, & OA). First on the

negative affect subscale, there was no main effect of Time, F (1,104) = 2.54, p = .114, η_p^2 =.002. However, there was a main effect of Group, F (2,104) = 13.77, p < .001, η_p^2 =.021. Bonferroni post-hoc testing found OA had significantly lower negative affect scores compared to both YA controls (p_{bonf} < .001) and YA mTBI (p_{bonf} < .001). No differences were found between the YA groups (p_{bonf} = 1). Moreover, there was a significant interaction of Time x Group, F (2, 104) = 4.35, p = .015, η_p^2 = .209. Simple main effect analysis showed that for OAs, Time had an effect with OAs reporting greater negative affect scores post study compared to pre-study, F (1,35) = 5.328, p = .027. For YA mTBIs, the effect of Time was not significant, indicating no increase in negative affect post study, F (1,36) = 3.613, p = .066. This effect was not present in YA controls (p = .156). See Figure 8 for breakdown of interaction. For the positive affect subscale, there was a main effect of Condition, F (1, 104) = 10.53, p = .002, η_p^2 = .209, such that positive affect scores were significantly reduced post experiment relative to pre-experiment All other main effects and interactions were nonsignificant (p > .05).

Figure 8

PANAS negative affect scores before and after the experiment, in each Group



2.7 Discussion

Prior research has shown that individuals with a chronic history of mTBI have persistent affective and cognitive symptoms that continue months to years beyond injury (Dikman et al., 2017; Ponsford et al., 2000; Ruff et al., 1996; Sigurdardottir et al.; 2009, Theadom et al., 2016;). As such, finding a unique cognitive signature for mTBI has been elusive and the purpose of the present study was to merge both research on aging and mTBI

because both populations share similar cognitive complaints and vulnerabilities to frontal and temporal lobe connectivity. The present study therefore had two overarching goals: 1) to assess associative memory in mTBI and compare it to a known population with associative deficits (e.g., older adult), and 2) to explore affective and fatigue responses to cognitively demanding task.

Contrary to our initial hypothesis, mTBI did not show impairment on either item or associative memory, even when encoding was completed under divided attention compared to YA Controls. However, the mTBI group did show a greater numerical decline in their corrected recognition scores for the associative memory test when comparing performance under full and divided attention (see Table 4). This was shown by significantly greater difference in memory scores on the associative memory test from the full to divided attention, compared to both YA Controls and OAs (see Figure 4). However, these results should be interpreted cautiously since there was no significant three-way interaction and were completed based on a priori predictions. These findings suggest a numerical trend and that larger samples are needed to verify if the effect is present. Previous studies using pictorial scene-object associations (Mangels et al., 2002) or verbal category-target associations (Blanchet et al., 2009) found a disproportionate difference between these groups in a divided attention condition. Unlike the previous studies, this study sought to directly assess associative memory independently from item memory. The choice to use unrelated word-pair lists to assess associative memory in the present study likely made the task more difficult and may have resulted in poorer performance across all groups, preventing us from

finding the strong group differences between YA groups that has been shown in previous work.

The previous studies only included a young adult sample and when you remove older adults from analysis and only compare young adults the critical three-way interaction of Test Type x Attention x Group was not significant (p = .06), though trends in the direction of replicating previous findings. These results can be found in Appendix D. This trend is driven by the YA control group having a smaller proportionate drop in the associative memory test when encoding was completed under divided attention compared to full. This suggests that YA Controls may be better equipped to cope with reduced attentional resources on the more difficult test compared to YA mTBI. However, these conclusions must be taken cautiously as with a larger sample size this trend may vanish or appear more robustly.

2.7.1 Associative Deficit in Older Adults

Our findings support the claim of an associative deficit in older adults, as initially proposed by Naveh-Benjamin (2000). He found that both young adults and older adults show a significant decline in memory performance for associative rather than item memory. However, the degree of the deficit is more pronounced in older adults, leading to a larger proportional drop compared to young adults. As shown in Figures 2 & 3, item memory was comparable between all three groups, however older adults demonstrated a greater drop in memory performance between the two Test Types than both young adult Groups.

2.7.2 Fatigue & Affect

OAs reported slower response times throughout the course of the study. The slower response times are partially expected because of OAs reduced literacy of working with computers and keyboards compared to YAs. We found no differences across groups in terms of fatigue, though there was a negative relationship in the mTBI group between mental fatigue scores and their performance on the divided attention item memory This relationship suggests there may be an increase in fatigue in those with chronic mTBI, after they complete a demanding cognitive task, that reduces their ability to cope compared to YA controls. It also indicates that effects from fatigue may only be observable behaviourally when participants reach their individual threshold for cognitive resource requirements. Thus, fatigue effects are difficult to assess in a large group where individual differences in post injury resource limitations increase within-group variability. Though, the additional data gathered from mass testing showed trait level differences in attentional lapses when comparing ARCES scores from the mTBI group to Controls. These findings corroborate the common complaints in chronic mTBI of lingering cognitive difficulties.

2.7.3 Limitations

The present study has a few limitations, largely that TBI history is self-reported and completed months to years after injury. Previous research has warned that self-reported symptomology can not always be fully accurate (Ruff et al., 2009). This was highlighted by issues of internal consistency between what participants reported on their pre-screen and in-lab. Moreover, a considerable proportion of the mTBI group (n = 21) did not report having PTA or LOC, which would not meet both the ACRM (1993) and WHO (Carroll et al., 2004)

requirements for an mTBI to have at least one of these symptoms present. Additionally, LOC has been shown to be a distinguishing factor due to the exacerbation of white matter damage when consciousness is lost (Sorg et al., 2014). Therefore, our mTBI group may be too heterogeneous to confidently distinguish from our control group, and any injuries are much milder than would be sufficient to meet mTBI requirements.

2.7.4 Conclusion

Overall, when you expand previous findings of deficits in associative learning under divided attention (e.g., Blanchet et al., 2009; Mangels et al., 2002) to a traditional associative deficit paradigm using semantically unrelated word-pairs, the findings replicate. Patterns of data show that the cognitive profile of those with a remote mTBI falls somewhere between a YA Control and Older Adult group. We found that the drop in recognition accuracy from full to divided Attention conditions, on the Associative memory test was significantly greater in mTBI compared to young controls and was like that seen in older adults. In terms of psychological measures, we found that self-reported mental fatigue increased significantly, only in the mTBI group, as performance on the Associative test under divided attention decreased. Our findings suggest that individuals with a remote mTBI, like older adults, have a tougher time coping when tasks increase in cognitive demand, and that cognitive tasks may be experienced as more demanding in mTBI groups, even months after injury.

Chapter 3
Experiment 2: Online Study of Cognitive Impairment in Chronic mTBI and Older Adults

3.1 Background & Hypothesis

The COVID-19 pandemic put in-lab research into a precarious situation when laboratory facilities became restricted. However, it did present an opportunity to recruit participants efficiently using crowdsourcing platforms (e.g., Prolific, Amazon's Mechanical Turk, etc.). As it pertains to my thesis, no study of cognitive and affective dysregulation has been conducted online, in individuals who have a remote history of a mTBI. Moreover, these circumstances allowed for the potential recruitment of sample sizes far exceeding those in past studies. Thus, the decision was made to run an online remote study in conjunction with the in-person study presented in Chapter 2. This was also made necessary because of the initially slow in in-person recruitment that presented concerns about the possibility of completing an in-person experiment with an adequate sample size within the required period for this Master's thesis.

Being a companion study, the hypotheses and objectives remained consistent with what was already discussed in Chapter 2. Though, the caveat with online studies is the suspected loss of experimental control without the rigid parameters that are typical in an in-person laboratory setting. For example, the participant can ask clarification questions if they are unsure of the procedure. Additionally, the researcher can make observations of the participants actions and intervene if there is a problem or if the instructions are not being

followed correctly. The lab setting also allows for a controlled environment with standard instruments (i.e., computers, keyboards, monitors, etc.) and free from distractors.

Running online studies poses challenges for researchers regarding data quality, participant engagement and gathering accurate and representative samples (Newman et al., 2021). Therefore, the aims of the present study were more exploratory in nature given these concerns with online data collection. In addition to being a pioneering study in mTBI online, Experiment 2 represents one of the first studies to explore the associative memory deficit (Naveh-Benjamin, 2000) in an online older adult sample.

3.2 Methods

3.2.1 Participants

The participants for this experiment were recruited through *Prolific* (www.prolific.co, London, UK), an online crowdsourcing platform for participant recruitment. Participants were placed into three groups: a young adult (YA) control group, a young adult with history of mTBI group, and a healthy older adult (OA) group. All participants completed the study online remotely and without intervention from the experimenter and were paid £5.34 for their participation. The study was conducted over a 5-month period from April 2022 through to August 2022. We recruited a total of 112 participants and included the data from 103 participants in the statistical analysis. The remaining 9 participants were removed because of conflicting report of incidence of mTBI (n = 4), concurrent acute mTBI (n = 1), and poor performance (n = 4) (corrected recognition score under full attention below 0). In total, 38 YA Controls, 35 YA mTBI, and 30 OAs were included in the final sample. Furthermore,141

additional participants attempted, but did not complete, the study in its entirety for a variety of suspected reasons (e.g., too difficult, too complicated, loss interest, etc.). On Prolific, these are recorded as returned their submission and aborted their study attempt before completing. Thus, the remaining sample is prone to survivorship bias, as performance in those who were unable to complete the study are overlooked.

3.2.2 Inclusion and Exclusion Criteria

Prolific requires participants to complete a comprehensive pre-screen before they are granted permission to access studies. This pre-screen information was used to set the inclusion and exclusion criteria for the present study. To be included in the study, the YA were required to be between 18 and 25 years old to match the age cutoffs from Experiment 1. Additionally, OAs were required to be 65+ years old. Participants must have indicated that their first language was English and were limited to those who self-reported as residing in the United Kingdom (n = 63), the United States (n = 23), Canada (n = 10), Ireland (n = 5), Australia (n = 2), and New Zealand (n = 0). These countries were selected because of their similar cultural and language profile. Finally, the participants had to be using a Window-based computer operating system because the E-Prime experiment file is unable to be run through alternative operating systems such as Mac OSX or Linux.

For the YA Control group, they had to indicate they had no previous head injury. However, for the YA mTBI the pre-screen questions used by Prolific were limited in scope of previous history of head injury beyond having the participant declaring yes or no to having sustained a previous head injury. Therefore, an additional pre-screen ‘study’ was created and posted on

Prolific that was only visible to users who were identified as having a previous head injury. Participants were asked about their head injury history including when the injury occurred, how many they had, and whether they experienced LOC or PTA. A total of 434 participants completed a brief pre-screen study. Those who sustained an injury 3 to 48 months prior and who met the criteria for a mTBI (based on ACRM guidelines) were invited to participate in the full study by having the follow up study made visible to them. Eligible participants were also encouraged to participate through a direct message within the Prolific system. For the OA group, the only unique additional restrictions were a self declaration that they have no present mild cognitive impairment or dementia, and that they were between 65 and 99 years old.

3.3 Measures

The present study repeated many of the same measures as in Experiment 1. The stimuli were the same and participants were administered the Mill-Hill Vocabulary Scale (Raven, 1958), Concussion History Questionnaire, Positive and Negative Affect Schedule (Thompson, 2007), and Description of Feelings Questionnaire. However, they were not administered the National Adult Reading Test (North American Revision) (Blair & Spreen, 1989) or the Montreal Cognitive Assessment (Nasreddine, 1986) because both must be administered directly by the experimenter and cannot be completed remotely. Additionally, the Concussion History Questionnaire was modified to ask participants to estimate number of months since injury to get a more accurate continuous measure of injury time. Instead, the

Cognitive Failures Questionnaire (Broadbent et al., 1982) was administered in OA in substitute for the MoCA.

3.3.1 Cognitive Failures Questionnaire

The Cognitive Failures Questionnaire developed by Broadbent et al., (1982) is a self-report questionnaire asking participants the frequency of lapses in attention, perception, memory, motor functioning and cognition in their everyday lives. This scale was only given to the older adult group to get an assessment of their perceived cognitive functioning. The questionnaire consists of 25 items comprising of everyday cognitive mistakes and respondents are asked to report how frequent these mistakes occur from *never* (0) to *very often* (4) in the previous six-month period. The total score is calculated by summation of all answers with a range between 0 and 100, with a higher total score indicating more subjective cognitive failures. A high score is defined as $\geq$ 43. Furthermore, follow up studies by Rast et al. (2009) determined all items load onto three distinct factors: *forgetfulness, distractibility, and false triggering*. The summation of scores across these factors yields three subscale scores.

3.4 Demographic Characteristics

Demographic information and neuropsychological tests for each group, to characterize the sample can be found in Table 8 and Table 9. In the young adult samples, 57.89% of the YA Controls (n = 22) and 60.00% of the YA mTBI (n = 21) reported currently being students. Independent samples t-test showed that OAs had significantly higher MHV scores than YA controls, t (66) = 5.00, p <.001, d = 1.22, and YA mTBI, t (63) = 5.70, p <

.001, d = 1.42. The YA groups did not differ on MHV scores (p = 0.36). Again, these findings are typically found in previous studies of cognitive effects of aging (e.g., Ben-David et al., 2015; Verhaeghen, 2003), and replicates what was found in Experiment 1. All three groups reported similar years of education (p > .37).

Table 8

Experiment 2: Demographic characteristics of study sample

	Young Adult Controls		Young Adult mTBI		Older Adults	
	M	*SD*	*M*	*SD*	*M*	*SD*
Age	21.9	2.1	21.9	2.1	68.6	3.3
Years of Education	15.5	1.9	15.9	2.5	16.1	3.4
MHV Score	18.4	3.8	17.6	4.0	23.0	3.6
Number of mTBIs			2.23	2.21		
Months since Injury			37.13	35.51		

Note. MHV = Mill Hill Vocabulary Scale.

Table 9

Experiment 2: Demographic frequencies of study sample

Study Group	Handedness	Frequency	Percentage
YA Controls	Ambidextrous (Both)	0	0.00
	Left	5	13.16
	Right	33	86.84
	Total	38	
YA mTBI	Ambidextrous (Both)	2	5.71
	Left	3	8.57
	Right	30	85.71
	Total	35	
OA	Ambidextrous (Both)	0	0.00
	Left	0	0.00
	Right	30	100.00
	Total	30	
	Sex		

Study Group	Handedness	Frequency	Percentage
YA Controls	Female	19	50.00
	Male	19	50.00
	Intersex	0	0.00
	Total	38	
YA mTBI	Female	14	40.00
	Male	20	2.86
	Intersex	1	57.14
	Total	35	
OA	Female	14	46.67
	Male	16	53.33
	Intersex	0	0.00
	Total	30	
	Gender		
YA Controls	GQ/GNC/GNB/GF	0	0.00
	Man/Transman	19	50.00
	Woman/Transwoman	18	37.14
	Prefer not to answer	1	2.63
	Total	38	
YA mTBI	GQ/GNC/GNB/GF	2	5.71
	Man/Transman	20	57.14
	Woman/Transwoman	13	37.14
	Total	35	
OA	GQ/GNC/GNB/GF	0	0.00
	Man/Transman	16	53.33
	Woman/Transwoman	14	16.67
	Total	30	

Note. GQ/GNC/GNB/GF = Genderqueer/ Gender non-conforming/ Gender non-binary/ Gender fluid

3.4.1 Clinical TBI Characteristics

TBI history was taken from the Concussion History Questionnaire for all participants. For the YA mTBI group (n = 35) the self-reported number of concussions sustained ranged from 1 to 11, with an average of 2.23 (SD = 2.21). Participants were instructed to report symptomology for only their most recent TBI. TBI injury history was taken from participants

second assessment during study. Time since injury ranged from 1.5 months to 125 months post-injury, with an average of 37.13 (*SD* = 35.51). To increase participant numbers the there was no upper bound and participants over 48 months were invited to participate. Two participants were reported to be in the acute stage (< 3 months post-injury), while the remainder were in the chronic stage (>3 months post-injury). LOC was reported in 10 cases: 1-59 seconds (*n* = 6), 1-5 minutes (*n* = 5), while one participant declared not knowing. PTA was reported in 8 cases: 1-59 seconds (*n* = 2), 1-60 minutes (*n* = 5), 1-24 hours (*n* = 1), while one participant declared not knowing. In total, 13 participants reported having no LOC *and* no PTA, while 6 participants reported having *both* LOC and PTA. Additional mass testing data of the DERS, DASS, and ARCES were not collected in Experiment 2 (in Experiment 1, these scales were taken from SONA through a separate pre-screen measure).

3.5 Procedure

Participants were assessed individually on their own computers remotely without intervention from the experimenter. The study followed the same procedure as Experiment 1, with a few modifications. First, the instructional slide show was instead shown as a pre-recorded narrated presentation detailing the study instructions and memory tasks. In the video participants were shown two word-pairs followed by an example of the item recognition memory test and the associative recognition memory test. In the simulated item recognition test participants were shown one word at a time and were instructed to either indicate if the word was OLD (shown in the original list) or NEW (never shown in the original list) by pressing the Z key for OLD and the C key for NEW on their keyboard. In the

simulated association recognition memory test, the participants were instead shown word-pairs and were instructed to indicate if the word-pair was OLD (intact word-pair shown in the original list) or NEW (rearranged words from the original list that were not presented together). Again, participants were told to press the Z key to indicate an OLD response and the C key to indicate a NEW response. Throughout the video presentation the participants were guided through the correct response for each simulated test item.

After completing the video, participants were asked to download an *E-PrimeGO* (Version 1.0.1.44, Pittsburgh, PA) experiment package to run locally on their computer. Next, participants were first introduced to the attention manipulation and were instructed that while learning one of the lists they would have to multi-task by simultaneously completing a digit-monitoring task. The digit-monitoring task consists of a continuous string of numbers between 10-99 every 2 seconds in a pseudo-random order. Participants were told to press the Y key every time they heard three odd numbers spoken in a row. A baseline digit task was completed before advancing to the experimental phase. These instructional and practice trials allowed the participant to become familiar with the experimental phase of the study.

The experimental phase of the study followed the exact procedure as Experiment 1. The final variation from Experiment 1 was that the OA group completed the Cognitive Failures Questionnaire (Broadbent et al., 1982) at the conclusion of the study to assess cognitive functioning instead of being administered the MoCA.

3.6 Results

Corrected recognition was used to assess participants memory performance. Corrected recognition is one's hit rate (HR) minus their false alarm (FA) rate. Tabulation of data was identical to Experiment 1 in Chapter 2.6.3.2. All statistical analyses were conducted using JASP (Version 0.17.1; Department of Psychological Methods, University of Amsterdam). Data transformations to a 90% Winsorization was completed identical to Chapter 2.

3.6.1 Recognition Performance

To examine differences in memory, a 2 x 2 x 3 mixed model ANOVA was completed for participants' corrected recognition (hit rate – false alarm rate) scores, with the repeated measure factors being Attention (Full vs Divided) and Test Type (Item vs Associative) and a between-subject factor of Group (YA Controls, YA mTBI, & OA). There was a significant main effect of Attention, such that recognition performance was greater under full compared to divided attention, F (1,100) = 146.54, $p < .001$, $\eta_p^2 = 0.59$. Furthermore, there was a significant main effect of Test-type, such that recognition performance was greater for the item test than the associative test, F (1,100) = 91.20, $p < .001$, $\eta_p^2 = 0.48$. There were no differences found between the group, F (1,100) = 0.06, $p = .944$, $\eta_p^2 < .001$. Likewise, there were no significant interactions. See Figures 9 and 10 for graphical representation of Test Type and Group, as was presented in Chapter 2. See Table 10 for hit rate, false alarm rate, and corrected recognition of each group.

Figure 9

Experiment 2: Associative test memory performance between Group

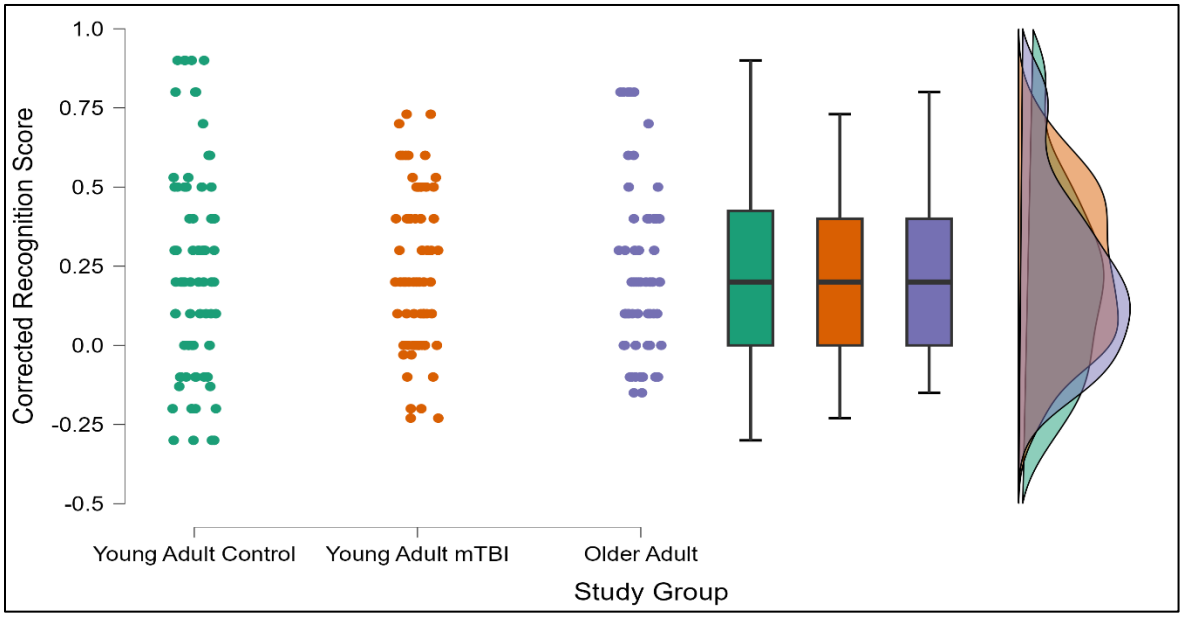


Figure 10

Experiment 2: Item test memory performance between Group

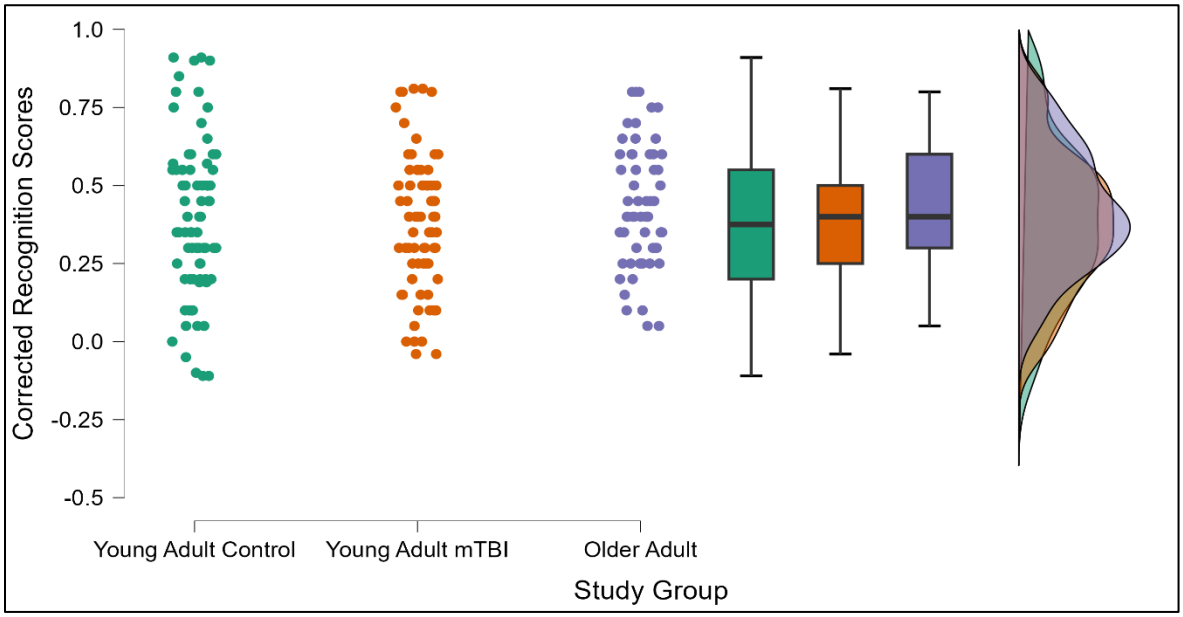


Table 10

Experiment 2: Recognition Scores on Memory Tests by Attention

Test Type	Attention	Study Group	HR	FA	CR
Item	Full	YA Control	0.74 (0.16)	0.20 (0.16)	0.54 (0.22)
		YA mTBI	0.75 (0.13)	0.25 (0.17)	0.51 (0.18)
		OA	0.71 (0.19)	0.18 (0.14)	0.53 (0.18)
	Divided	YA Control	0.60 (0.17)	0.34 (0.19)	0.25 (0.19)
		YA mTBI	0.61 (0.19)	0.37 (0.16)	0.25 (0.18)
		OA	0.58 (0.18)	0.24 (0.15)	0.33 (0.15)
Associative	Full	YA Control	0.60 (0.27)	0.22 (0.19)	0.38 (0.32)
		YA mTBI	0.65 (0.20)	0.32 (0.19)	0.35 (0.22)
		OA	0.62 (0.23)	0.29 (0.23)	0.33 (0.30)
	Divided	YA Control	0.43 (0.18)	0.34 (0.19)	0.08 (0.26)
		YA mTBI	0.55 (0.21)	0.41 (0.23)	0.13 (0.26)
		OA	0.40 (0.23)	0.31 (0.23)	0.10 (0.18)

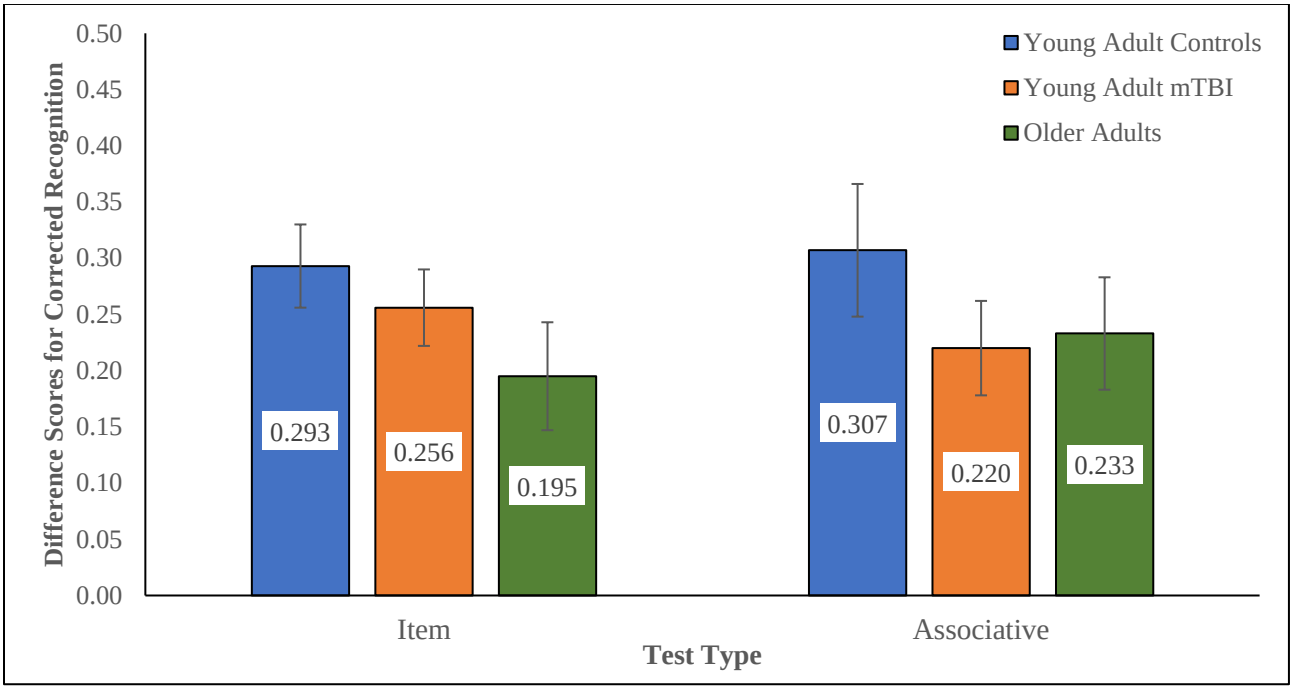
Note. Standard deviation is presented in parentheses. CR = Corrected Recognition. HR = Hit Rate. FA = False Alarm Rate. YA = Young Adult. OA = Older Adult

3.6.2 Difference Scores

Difference scores in memory performance were calculated in the same manner as in Chapter 2. Again, proportional difference scores were unable to be calculated because of issues with dividing by zero, therefore, we used raw difference scores. Based on a-priori predictions of differences between Study Group on Attention, independent samples t-tests were done to compare Groups on difference scores on the Item and Associative tests. No Group differences were found on difference memory scores for either Item or Associative test scores (see Figure 11)

Figure 11

Experiment 2: Difference memory scores between Group for each Test Type



Note. Error bars represent +/- 1 SE.

3.6.3 Distractor Task

A 2 x 3 mixed model ANOVA was completed to examine performance on the odd-digit monitoring distractor task. The hit rate for making correct endorsements of a sequence of odd numbers was the dependent variable. The repeated measure factor was Condition (baseline & dual-task) and the between-subject factor was Group (YA Control, YA mTBI, & OA). The data for 4 participants in the YA Control group are missing due to initial problems extracting keypresses from the experiment software. See Table 11 for odd-digit monitoring performance across all groups. Unexpectedly, there was no main effect of Condition, *F*

(1,96) = 0.108, p = 0.744, $\eta_p^2 < 0.001$, such that digit hit rate in the baseline, and during the dual task conditions, did not differ. Moreover, there was no main effect of Group, F (2,96) = 1.21, p = 0.301, $\eta_p^2 = 0.03$. Finally, there was a significant Condition x Group interaction, F (2,96) = 3.64, p = .03, $\eta_p^2 = .07$. Simple main effect showed this interaction was driven by the YA mTBI group having poorer performance on the task from baseline to dual task, F (1, 96) = 11.01, p = 0.002, while YA controls (p= 0.524) and OAs (p = 0.183) showed no difference in condition. Thus, the YA mTBI group showed a larger drop in the distractor task performance compared to the other groups.

Table 11

Experiment 2: Odd-digit monitoring distractor task hit rate performance

Study Group	Baseline Hit Rate	Dual task Hit Rate
YA Control	0.84 (0.24)	0.82 (0.22)
YA mTBI	0.78 (0.30)	0.71 (0.27)
OA	0.71 (0.34)	0.78 (0.29)

Note. Standard deviation is presented in parentheses.

3.6.4 Affective Measures

3.6.4.1 Fatigue

Fatigue measures were collected pre and post experiment using the Description of Feelings Questionnaire for all participants, except one in the older adult group whose affective measures data file was corrupted and could not be retrieved. The same process was repeated here as in Chapter 2, with four separate repeated measures ANOVAs being run for

each item, with the within-subject factor being Time (Pre & Post) and the between-subject factor being Group (YA controls, YA mTBI, and OAs).

For physical fatigue, there was no main effect of Time ($p = .550$). However, there was a main effect of Group, F (2, 99) = 11.870 $p < .001$, $\eta_p^2 = .193$. Bonferroni post-hoc testing showed that the OA group reported lower levels of physical fatigue than YA Controls ($p_{bonf} = .002$), and YA mTBI ($p_{bonf} < .001$). YA controls and YA mTBI did not differ ($p_{bonf} = .597$). No significant interactions were found.

For mental fatigue, there was a main effect of Time, F (1, 99) = 41.000, $p < .001$, $\eta_p^2 = .293$, such that mental fatigue scores were higher post study than pre study. There was also a main effect of Group, F (2, 99) = 12.714, $p < .001$, $\eta_p^2 = .204$. Bonferroni post-hoc testing showed that the OA group reported lower levels of mental fatigue than YA Controls ($p_{bonf} < .001$), and YA mTBI ($p_{bonf} < .001$). YA controls and YA mTBI did not differ ($p_{bonf} = 1$). No significant interactions were found.

For irritability, there was a main effect of Time, F (1, 99) = 21.421, $p < .001$, $\eta_p^2 = .178$, such that irritability scores were higher post study than pre study. There was a main effect of Group, F (2, 99) = 8.286, $p < .001$, $\eta_p^2 = .143$. Bonferroni post-hoc testing showed that the OA group reported lower levels of irritability than YA Controls ($p_{bonf} < .001$), and YA mTBI ($p_{bonf} = .002$). YA controls and YA mTBI did not differ ($p_{bonf} = 1$). No significant interactions were found.

For total fatigue scores, there was a main effect of Time, F (1, 99) = 29.388, $p < .001$, $\eta_p^2 = .229$, such that total fatigue scores were higher post study than pre study. A main effect of Group was found, F (2,99) = 14.573, $p < .001$, $\eta_p^2 = .229$. Bonferroni post-hoc testing

showed that the OA group reported lower levels of total fatigue than YA Controls (p_{bonf} < .001), and YA mTBI (p_{bonf} < .001). YA controls and YA mTBI did not differ (p_{bonf} = 1). No significant interactions were found.

3.6.4.2 Correlations

Correlational analyses were run within-group to compare proportional percent changes in fatigue items with each corrected recognition scores for each memory test. Proportional changes were calculated the same as in Chapter 2. There were no significant correlations for proportional change in physical fatigue or irritability. For mental fatigue in OAs, there was a significant correlation with corrected recognition on divided attention item test, r (29) = -.44 p = .018. Moreover, for total fatigue in OAs, there was a significant correlation with corrected recognition on the divided attention associative test, r (29) = -.38, p = .041. All mental and total fatigue score correlations were nonsignificant for YA controls and YA mTBI.

3.6.4.3 Mood

Independent ratings of positive and negative affect scores on the PANAS rated before and again after the experiment were tabulated. Two separate 2 x 3 mixed model ANOVAs were conducted, one for positive affect and one for negative affect scores, with the within-factor being Time (Before and After the experiment), and the between factor being Group (YA Controls, YA mTBI, & OA). For the negative affect subscale, there was no main effect of Time, F (1,99) = 0.05, p = .829, η_p^2 =.002. There was a main effect of Group, F (2,99) = 12.60, p < .001, η_p^2 =.203. Bonferroni post-hoc testing showed that OAs reported less

endorsement of negative affect compared to both YA controls ($p_{bonf} < .001$) and YA mTBI ($p_{bonf} < .001$). No differences were found between the YA groups ($p_{bonf} = 1$). Moreover, there was no significant Time x Group interaction ($p = .360$).

For the positive affect subscale, there was a main effect of Time, F (1, 99) = 17.77, $p < .001$, $\eta_p^2 = .152$, such that positive affect scores were significantly reduced post-experiment relative to pre-experiment. There was also a main effect of Group, F (2, 99) = 11.79, $p < .001$, $\eta_p^2 = .192$. Bonferroni post-hoc showed OAs reported higher positive affect scores compared to both YA controls ($p_{bonf} < .001$) and YA mTBI ($p_{bonf} < .001$). No differences were found between the YA groups ($p_{bonf} = 1$). Moreover, there was no significant Time x Group interaction ($p = .065$). See Table 12 for scores from the Description of Feelings questionnaire and PANAS for both pre and post study in each group.

Table 12

Experiment 2: Self-reported ratings of fatigue and affect pre- and post-experiment

Measurement	Time	Study Group	Mean
Physical Fatigue	Pre-Experiment	YA Controls	38.98 (25.55)
		YA mTBI	48.46 (27.86)
		OA	17.74 (21.49)
	Post-Experiment	YA Controls	40.73 (25.28)
		YA mTBI	47.03 (28.61)
		OA	20.42 (21.57)
Mental Fatigue	Pre-Experiment	YA Controls	43.22 (29.58)
		YA mTBI	44.26 (29.82)
		OA	15.61 (19.98)
	Post-Experiment	YA Controls	57.48 (27.43)
		YA mTBI	58.37 (28.01)
		OA	30.08 (28.66)
Irritability	Pre-Experiment	YA Controls	25.60 (26.20)
		YA mTBI	24.26 (24.90)
		OA	4.48 (5.19)

	Post-Experiment	YA Controls	32.36 (26.12)
		YA mTBI	31.55 (24.38)
		OA	14.86 (19.43)
Total Fatigue	Pre-Experiment	YA Controls	108.09 (74.52)
		YA mTBI	118.11 (66.25)
		OA	38.50 (40.33)
	Post-Experiment	YA Controls	130.49 (68.03)
		YA mTBI	136.90 (68.07)
		OA	64.70 (56.17)
Positive Affect (PANAS)	Pre-Experiment	YA Controls	14.92 (3.74)
		YA mTBI	15.51 (3.68)
		OA	19.00 (2.85)
	Post-Experiment	YA Controls	14.61 (4.08)
		YA mTBI	13.69 (4.14)
		OA	17.62 (3.17)
Negative Affect (PANAS)	Pre-Experiment	YA Controls	9.82 (3.90)
		YA mTBI	9.49 (4.00)
		OA	6.28 (1.85)
	Post-Experiment	YA Controls	10.24 (3.96)
		YA mTBI	9.17 (2.96)
		OA	6.31 (1.98)

Note. Standard deviations are in parentheses. Physical fatigue, mental fatigue, irritability, and total score have 90% winsorized transformation within-group.

3.7 Discussion

The ability to recruit participants efficiently online presented an opportunity to look at mTBI and aging that was unique in comparison to past published research studies. The primary aims and hypotheses of this experiment were the same as those presented in Chapter 2. The main difference was that data were collected remotely online. Moreover, the prospect of examining whether we could replicate the often reported 'associative memory deficit' in a sample of data from older adults collected online is, to our knowledge novel. Thus, the goal of Experiment 2 was to compare findings to those reported earlier for Experiment 1 collected in person. In so doing we report on the feasibility of collecting data documenting cognitive performance using online crowd sourcing databases.

3.7.1 Memory Performance

Corrected recognition scores showed that as participants moved from full to divided attention conditions, their performance dropped as expected. Similarly, as participants moved from completing Item to an Associative test, their performance also dropped. These experimental manipulations were expected to yield such results based on past research (Blanchet et al., 2009; Mangels et al., 2002). These results also lend support to the notion that the present paradigm was successful when completed online, and that Attention and Test Type main effects and interactions were replicable. Where the online study deviates from past findings (Blanchet et al., 2009; Mangels et al., 2002), as well as the results reported in Chapter 2 is in the Group effects. Across all three groups (YA Controls, YA mTBI, and OAs) their performance scores were matched regardless of condition (see Table 10). This meant the associative deficit in memory, typically reported in older adults failed to replicate in a sample recruited online. Furthermore, these findings also failed to replicate previous studies in YAs that explored associative memory in mTBI individuals under full and divided attention (e.g., Blanchet et al. 2009; Mangels et al., 2002).

3.7.2 Online Cognitive Studies

The inconsistency and failure to replicate previous findings is presumed to be a result of online data collection and the tribulations that are attached with it. It is possible these findings did not replicate because the samples were unique and was not representative of the population. We suspect this primarily because of three plausible factors. First, for the OAs, they are less computer literate than their YA counterparts and it is possible that they required outside assistance to complete the study; such ‘extra help’ would influence results. For

example, someone else could record or write down the to-be-remembered words rather than memorizing them. Future work could remedy this by video-recording participants for the duration of the study. Finally, at the time of data collection there was no formal process for validating a participant's actual age. As such it is possible that not all OA participants were indeed over the age of 65. These factors are speculative but provide insight into some of the pitfalls of running participants online through a cognitively demanding study.

3.7.3 Conclusion

The present study highlighted the benefits and the costs of running online studies early during the COVID-19 pandemic. Since data collection, many platforms have implemented measures to assist researchers in validating their sample and ensuring better data quality. The Group differences in cognitive and affective performance from Experiment 1 did not replicate in the present study. This discrepancy is suspected to be the result of poorer data quality from online data collection compared to the data collected in-person. However, as a pioneering study it was important to highlight some of the issues with online collection and provide insight into how future studies should be run to avoid some of these issues.

Chapter 4
General Discussion

The present thesis had four overarching goals: 1) to build upon previous articles investigating cognitive effects of a remote mTBI (e.g., Blanchet et al., 2009; Mangels et al., 2002) by exploring commonalities and differences in memory for individual words (items) and word pairs (associative) between young adults and young with chronic mTBI as well as healthy older adults (e.g., Naveh-Benjamin, 2000); 2) to examine and measure the costs to emotion regulation and fatigue that arise from completing a cognitively demanding task (e.g., Berginström et al., 2018); 3) to determine and characterize whether there is a common neurocognitive signature between chronic mTBI in young adults and older adults; and 4) to determine the feasibility and quality of data collected online in these populations.

Experiment 1 (Chapter 2) aimed to determine whether there exist commonalities in terms of cognitive performance in aging individuals and those with a history of mTBI. The reason for suspecting an overlap is because these populations have similar cognitive complaints and shared neuroanatomical vulnerabilities to the frontal and temporal lobe regions. Previous research within the young adult population have only showed reductions in memory between those who had a remote mTBIs and age-matched controls. In these studies, learning deficits of associations were observed in the mTBI group only when available attention was divided at encoding (e.g., Blanchet et al., 2009; Mangels et al., 2002). Previous studies in aging have shown deficits in associative memory regardless of any attention manipulation. Moreover, current theories of age-related decline in episodic memory suggest

this is due to atrophic aging effects, such as neuronal cell death, which hinder the ability to bind item to each other, or to a context, to form associations. This deficit has been reliably documented and is known as the associative deficit hypothesis (Naveh-Benjamin, 2000; Old & Naveh-Benjamin, 2008). The primary goal in this thesis was to reexamine previous findings documenting a similar associative deficit in YAs with chronic mTBI and compare them to a group of OAs who also show a strong decline in quality and quantity of associative episodic memories. Additionally, no previous studies of mTBI have examined performance of Item and Associative memory with pairs of unrelated words, the typical material used in a traditional associative memory paradigm (Naveh-Benjamin, 2000).

Experiment 1 found that YA controls and YA mTBI showed comparable memory for individual words (items) and word-pairs (associations) when encoding was performed under full as well as divided attention. However, examining the difference in memory performance, on an associative test, from full to divided attention showed that young with a remote mTBI had a greater drop in performance compared to both YA controls and healthy OAs. Again, these findings need to take with extreme caution given the lack of a three way and two-way interactions present, and analyses were only run based on prior predictions. As expected, OAs exhibited impairment in associative memory scores compared to both groups regardless of attention condition. This finding replicates previous research showing an associative deficit (Naveh-Benjamin, 2000). The finding of a deficit in memory for associations, reported here for unrelated word pairs, in the mTBI group replicates previous studies in this population in which the materials in the memory test consisted of pictorial scene-object associations (Mangels et al., 2002) and verbal category-target associations (Blanchet et al.,

2009). In those studies, as well as in my in-person sample of mTBIs (Chapter 2), memory was significantly poorer when initial encoding was done under divided compared to full attention.

Experiment 1 showed that memory performance in mTBI falls somewhere between age-matched YA controls and OAs. The difference across attention conditions, on the associative test, suggests that mTBI suffer primarily from impairments in executive control, or the ability to recruit sufficient attentional resources when dual tasking. This deficit converges with previous imaging and behavioural studies exploring the dysfunctionality of the frontal lobe region in mTBI (see Eierud et al., 2014 and Kim & Gean, 2011 for reviews of these studies). Previous studies examining the frontal lobes in mTBI have found traumatic axonal injuries in this area (Einarsen et al., 2019), particularly the dorsolateral and orbitofrontal cortices. The susceptibility of injury to this region from a mTBI has been hypothesized to arise due to the linear coup/contrecoup forces being applied to the front of the skull (Shaw, 2002). These areas serve a significant role in executive functioning and may explain why mTBI (in the current study and in previous research) display deficits in frontal lobe-type processes.

Notably, Experiment 1 showed that mTBI do not present entirely like OAs. If any associative deficits are present in mTBI they are secondary to deficits in executive control. These are similar conclusions to those made by Blanchet et al. (2009) and Mangels et al. (2002). This is because there was no difference between YA controls and YA mTBI in item or associative test performance when encoding was done under full attention; the deficit may only emerge when encoding was done under divided attention. In contrast, the OAs showed

the associative deficit regardless of whether encoding was performed under full attention or divided attention. Experiment 1 demonstrated that there is an impairment to cognition, in the mTBI group, when the task was made difficult, through divided attention and when the memory test was an associative one. Unlike the YA controls, the mTBI group was unable to cope with these increases in task difficulty.

The ability of an individual to also cope with cognitively demanding situations emotionally (such as needing to multi-task during encoding) was a secondary focus in Experiment 1. I considered the self-rated emotional and mental fatigue impact of completing such tasks. The study showed that OAs reported a greater increase in fatigue compared to both YA groups. This finding is to be expected given that aging is theorized to affect speed of processing and availability of attentional resources required to complete cognitive processes (Craik & Byrd, 1982; Salthouse, 1996). In mTBI, an interesting correlation was found showing that memory performance on the hardest task (divided attention, associative test) decreased as proportional fatigue scores increased The YA mTBI group was the only one to show this relationship, leading to the conclusion that performing well on this test was directly associated to one's ability to cope with the additional cognitive load. It is possible that fatigue effects had a greater influence on the memory performance of mTBIs compared to controls.

4.1 Cognitive Reserve Theory

One of the possible explanations for the differences in fatigue and memory scores is related to *cognitive reserve*. Cognitive reserve theory (Stern, 2002; 2009) is a concept that

stems from the idea that in cases where there is brain atrophy or damage (e.g., Alzheimer's disease, Huntington's Disease, mTBI), it does not always appear to manifest in direct connection with clinical observations. The brain attempts to cope with the injury by recruiting pre-existing cognitive processes and/or compensatory processes (Stern, 2002). Individual differences in these reserves have been therefore suggested to explain why some individuals who endure an mTBI recover more rapidly than others. This claim has been suggested by the finding that patients with Alzheimer's disease develop the onset of symptoms sooner if they have lower cognitive functioning (Jacobs et al., 1994).

Recently, there has been growing research on the role of cognitive reserve on the development of symptoms beyond the acute stage of TBI. A major limitation is the operationalization of cognitive reserve itself, since is lacks a direct quantifiable measure. Often, cognitive reserve is defined and measured through proxies such as pre-morbid IQ and education level. In a recent meta-analysis by Mathias & Wheaton (2015) looking at outcomes of TBI across varying levels of severity (32 of 90 included studies contained complete or partial mild samples), they found slightly more favourable outcomes in those with higher levels of cognitive reserve, as measured through years of education and premorbid IQ.

A limited number of studies have assessed the relationship between cognitive reserve and cognitive dysfunction in mTBI. In an acute stage longitudinal study (Stenberg et al., 2020) from 2 weeks to 3 months post injury, it was found that estimated levels of intelligence moderated the differences in cognitive functioning outcomes. This work suggests that individuals with lower cognitive reserve are more vulnerable to poorer cognitive outcomes (Stenberg et al., 2020). Additional studies looking beyond 3 months post injury have also

shown that lower cognitive reserve, either measured through intelligence or education levels, predicts poorer cognitive outcomes (Oldenburg et al. 2016). However, Anderson & Martin (2023) found cognitive reserve does not predict symptoms when you control for psychological distress and sex.

The idea that mTBI results in diminished cognitive reserve is a potentially new and promising path of research to assist in providing explanations to why some mTBI patients report persisting cognitive complaints, while others appear to recovery more rapidly. Although important, cognitive reserve was not a primary consideration of the present thesis, due to the homogeneity of undergraduate students preventing meaningful comparisons within group on index measures such as years of education and premorbid IQ. Cognitive reserve should be a consideration in future research.

4.2 Online Data Collection

Experiment 2 (Chapter 3) provided a unique opportunity to recruit many participants quickly and efficiently online using the platform *Prolific*. The rationale and aims for this study were the same as Experiment 1, though with the added element of running mTBI and OA groups online, something that has been seldom attempted before the COVID-19 pandemic. The findings from Experiment 1 to 2 did not fully replicate, with group differences not being present in Experiment 2.

Online platforms, such as *Prolific* have since updated and expanded the options for researchers since Experiment 2 was completed in the COVID-19 pandemic during stay-at-home orders in April 2022, in Ontario. For example, researchers can now require participants

to record the duration of their study involvement and submit video recordings of themselves doing the study, so that an experimenter can verify demographics and task compliance. These measures eliminate some of the concerns pertaining to participant validity and provide a window into participants' environment that is comparable to in-person data collection. Thus, while the lack of replication in Experiment 2 is interesting, it should not dissuade from the findings in Experiment 1. The data quality in Experiment 1 was greater than in Experiment 2 and warrant more meaningful conclusions about the study groups, however, sample sizes in both studies are still relatively small. Nonetheless, future research should investigate if theories such as the associative deficit hypothesis in aging, reliably replicate online, or whether this phenomenon is entirely ascribed to data quality.

4.3 General Limitations of mTBI Recruitment

The studies in this thesis are subject to a few limitations, principally in the recruitment and characterization of the mTBI groups. Previous research (see review by Ruff et al., 2009) has warned about the reliability of the self-reporting of TBI incidents. For example, acute symptoms such as post-traumatic amnesia can persist beyond other symptoms leading to issues recalling if other symptoms were present at time of injury. This is especially important since LOC has been suggested to be one of the indicators for the presence of neurocognitive problems (Sorg et al., 2014). Additionally, participants in my thesis sometimes reported having had more than one TBI and were asked to report only the symptoms of their most recent injury. Thus, their full brain injury history is unknown. There is a possibility that they experienced a more severe injury previously that could explain any

impairments. Moreover, GCS scores were not collected for mTBI participants, which is one of the defining criteria for TBI severity according to the ARCM and WHO definitions. Finally, a sizable proportion of the sample in Experiment 1 (n = 16, 58%) and Experiment 2 (n = 13, 37%) could be considered *subclinical* as they did not meet the requirements of the presence of LOC or PTA. However, group differences in Experiment 1 were still found indicating that even chronically subclinical mTBI participants can have cognitive impairments that persist months and years after injury. These factors emphasize some of the challenges of generalizing mTBI severity that result in a more heterogenous sample.

The heterogeneity inherent in mTBI samples may not entirely be problematic. TBIs represent a spectrum, and the less severe cases are frequently overlooked in the literature since they often produce less reliable results and noisier data patterns. In addition, the common definitions used for mTBI attempt to operationalize injury severity through rigid symptomology reports; this means that many individuals who self-report a head injury do not meet the clinical requirements for an mTBI. Thus, the inclusion of *subclinical* participants may be more representative of the population and allow for more generalized findings of the impact of mTBI and sub-mTBIs on neurocognitive and affective processes.

4.4 Conclusion

This thesis provides evidence that a remote mTBI is associated with lingering cognitive impairments, months to years after injury. Importantly, we found that the drop in recognition accuracy from full to divided Attention conditions, on the Associative memory test was significantly greater in mTBI compared to young controls. We also replicated the

known ‘associative memory deficit’ in our older adult sample in Experiment 1, but not 2. In terms of psychological measures, we found that self-reported mental fatigue increased significantly, only in the mTBI group, as performance on the Associative test under divided attention decreased. Our findings suggest that individuals with a remote mTBI, like older adults, have a tougher time coping when tasks increase in cognitive demand, and that cognitive tasks may be experienced as more demanding in mTBI groups, even months after injury.

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Appendix A

Study Word-Pair Lists

Practice Phase Word-Pairs (4 Pairs)

Bat	Hip
Jam	Fox
Gas	Boy
Rod	Cup

Word Pair List I (40 Pairs)

Hammer	Goose
Javelin	Bench
Spur	Boar
Saddle	Teeth
Luggage	Ankle
Stool	Dresser
Marble	Liver
Squid	Pencil
Faucet	Whale
Shirt	Drill
Fiddle	Watch
Store	Kayak
Engine	Hatchet
Harness	Tomato
Toaster	Pigeon
Bucket	Plane
Shoes	Wrench
Garlic	Button
Cane	Wallet
Knee	Table
Finger	Leather
Tower	Reptile
Jelly	Staple
Cork	Nurse
Folder	Arrow
Gate	Purse
Screw	Actor

Helmet	Paper
Compass	Stomach
Yacht	Knife
Puddle	Magnet
Harp	Locker
Vehicle	Nose
Curtain	Weed
Gorilla	Eraser
Fleece	Arena
Lantern	Trailer
Tofu	Keyhole
Shield	School
Celery	Jaguar

Word Pair List II (40 Pairs)

Elbow	Tunnel
Cabin	Sponge
Atom	Cactus
Crown	Kettle
Carrot	String
Plumber	Clock
Letter	Falcon
Jury	Ostrich
Pebble	Raven
Zipper	Fossil
Torch	Mitten
Truck	Lion
Meteor	Anchor
Swamp	Hairpin
Pocket	Stone
Belt	Alien
Hive	Flour
Insect	Teapot
Mouth	Llama
Stove	Garage
Glacier	Path

Scooter	Wheat
Paddle	Bean
Wheel	Field
Printer	Robe
Spinach	Ruler
Radio	Turkey
Rooster	Maid
Oatmeal	Jeans
Crayon	Shark
Lamp	Railway
Tuba	Oyster
Sheep	Machine
Tank	Mouse
Peanuts	Raft
Beaver	Temple
Ninja	Broom
Tractor	Acorn
Glue	Shelf
Camel	Iron

Foil Words for Item Recognition Test (40 Words)

Foil List I	**Foil List II**
Rake	Octopus
Chair	Domino
Nail	Pier
Gloves	Lung
Token	Wagon
Foam	Wire
Jacket	Subway
Barrel	Glass
Bladder	Lasso
Cave	Image
Kidney	Package
Adult	Rocket
Vein	Shed
Hamster	Plate
Disk	Stew

Coyote	Shampoo
Yolk	Bottle
Mill	Marker
Raccoon	Tiger
Napkin	Mirror

Buffer Word Pairs Placed at Beginning and End of Word Pair Lists (8 Pairs)

Vacuum	Taxicab
Journal	Dock
Office	Puppet
Spoon	Ladder
Factory	Eyebrow
Cannon	Basket
Lettuce	Iguana
Cabbage	Moth

Appendix B

Neuropsychological Testing Measures

Concussion History Questionnaire

How many concussions (a blow to the head) have you sustained?

_____

Please choose one option for each question below (if you have sustained multiple concussions, please answer in regards to your most recent one).

Have you ever had a concussion (a blow to the head)? If so, did you lose consciousness for:
- This question does not apply to me
- 0 seconds (did not experience loss of consciousness)
- 1–59 seconds
- 1–5 minutes
- 5–15 minutes
- 15–30 minutes
- greater than 30 minutes

When did the concussion occur?
- This question does not apply to me
- less than 3 month ago
- 4-12 months ago
- 1 year ago
- 2 years ago
- 3 years ago
- over 3 years ago

If you have had a concussion, did you experience confusion (Inability to focus attention) for:
- This question does not apply to me
- 0 seconds (did not experience)
- 1–59 seconds
- 1–60 minutes
- 1–24 hours
- greater than 24 hours
- I do not know

If you have had a concussion, did you experience disorientation

(Difficulty with regard to direction or position / loss of physical bearings) for:
- This question does not apply to me
- 0 seconds (did not experience)
- 1–59 seconds
- 1–60 minutes
- 1–24 hours
- greater than 24 hours
- I do not know

If you have had a concussion, did you experience loss of memory (brief amnesia) for:
- This question does not apply to me
- 0 seconds (did not experience)
- 1–59 seconds
- 1–60 minutes
- 1–24 hours
- greater than 24 hours
- I do not know

Description of Feelings Questionnaire

Please place the slider to how much you agree with the following statements from 1 (strongly disagree) to 100 (strongly agree).

	0 **100**
I feel physically fatigued right now	
I currently feel mentally drained	
I feel irritable at the moment	

Appendix C

Experiment 1: First Language Characteristics

Table C1

Frequencies for First Languages in Participants

Study Group	First Language	Frequency	% Of Group
YA Controls	English	22	61.11
	Arabic	1	2.78
	Farsi	1	2.78
	Hindi	4	11.11
	Persian	2	5.56
	Punjabi	1	2.78
	Sindhi	1	2.78
	Urdu	1	2.78
	Vietnam	1	2.78
	Cantonese	1	2.78
	Mandarin	1	2.78
	Total	35	100.00
YA mTBI	English	28	77.78
	Farsi	1	2.78
	French	1	2.78
	German	1	2.78
	Korean	2	5.56
	Russian	1	2.78
	Sinhala	1	2.78
	Cantonese	1	2.78
	Total	35	100.00
Older Adults	English	30	85.71
	Chinese	1	2.86
	German	1	2.86
	Italian	1	2.86
	Tamil	1	2.86
	Ukrainian	1	2.86
	Total	34	100.00

Appendix D

Experiment 1: Results with Young Adult Groups Only

For corrected recognition memory scores, a 2 x 2 x 2 ANOVA was completed identical to what was presented in Section 2.6.4, without the inclusion of the OA group. The unique finding of the ANOVA was a three-way interaction of Test Type x Attention x Group, which approaches significance F (1, 70) = 3.571, p = .063, η_p^2 = .049. Simple main effect analysis found the interaction was driven by YA controls not showing a decline across divided Attention when test type was collapsed (p = 0.146), while all other simple effects were significant (p < .01). These results suggested that YA controls could cope better under divided attention compared to YA mTBI.