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The Roles of Cognitive Reserve, Brain Reserve, and Psychological Resilience in Predicting Trajectories of Post-Concussive Symptoms in Children with Concussion and Orthopaedic Injury

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by

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Abstracts

Study 1

Objective. The current scoping review collated published research examining cognitive and brain reserve, as well as psychological resilience, in the context of traumatic brain injury (TBI) to address the following aims: (1) identify constructs and associated tools measured as proxies of reserve and resilience, (2) explore construct validity and mechanisms of reserve and resilience, as related to TBI, (3) describe relationships among reserve and resilience in the context of TBI, and (4) identify outcomes of TBI predicted by reserve and resilience. **Methods.** Specific search criteria were entered into MEDLINE Ovid and PsycINFO Ovid databases to capture relevant original research studies from inception to April 2020. Search results underwent title and abstract screen, as well as full-text review, to identify original research studies that examined the roles of cognitive reserve, brain reserve, or psychological resilience in individuals with TBI. **Results.** A total of 47 articles met inclusion criteria and were included in the review. The majority of studies examined cognitive reserve or resilience, and only one study examined brain reserve. Cognitive reserve was primarily measured via estimated pre-morbid intelligence, education, or occupational attainment using a variety of measures; brain reserve was measured via total intracranial volume; and resilience was primarily measured via a variety of self-report measures capturing individual/psychological factors associated with resilience. Studies supported brain reserve as a static factor and cognitive reserve and resilience as dynamic factors, and indicated reserve and resilience to be protective factors in a variety of cognitive, psychological, and social outcomes associated with TBI. **Conclusions.** Results elucidate current understandings of the roles of reserve and resilience in the context of TBI, as well as identify knowledge gaps that remain to be addressed. The results may aid in guiding future research studies directed towards improving prognosis and treatment of TBI.

Study 2

Objectives. The current study sought to examine the roles of psychological resilience, cognitive reserve, and brain reserve as predictors of and moderators of group differences in trajectories of post-concussive symptoms (PCS) among children with concussion and orthopaedic injury (OI). **Methods.** This study was completed as part of a larger parent study. A total of 465 children/adolescents, aged 8-17 years, and their caregivers were recruited prospectively from emergency departments across Canada after sustaining a concussion (n = 304) or OI (n = 161). Participants were followed for 6 months and were assessed at 3 time points: post-acute (i.e., approximately 10-days post-injury) and 3- and 6-months post-injury. Participants completed magnetic resonance imaging, which provided a measure of total brain volume (TBV), and a measure assessing psychological resilience during the post-acute assessment. Intelligence (estimated Full Scale IQ) was assessed during the 3-month assessment. Child- and parent-reported cognitive and somatic PCS were measured at all three time points. Linear mixed models were conducted to examine the effect of psychological resilience, IQ, and TBV as predictors and moderators of group differences in trajectories of PCS. **Results.** Primary analyses indicated that group, sex, age, retrospective ratings of pre-injury symptoms, and psychological resilience were predictive of individual differences in PCS; however, only group and pre-injury symptoms predicted changes in PCS across time and no moderation effects were found. **Conclusions.** Psychological resilience is an important predictor of PCS, regardless of injury type. However, cognitive reserve and brain reserve, which might be conceptualized as “neurological resilience”, may be less relevant in the context of minor injuries that have relatively little direct impact on neurological function. Results provide important implications for the implementation of resilience intervention efforts to help mitigate PCS and their negative consequences.

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Preface

Concussion is defined as a form of mild traumatic brain injury induced by biomechanical forces that results in functional disturbance in the absence of structural changes observed on conventional neuroimaging (McRory et al., 2017). Concussion is a common problem among children and youth, and often results in an array of physical, psychological, and cognitive sequelae, termed post-concussive symptoms (PCS). Diagnosis and treatment of concussion has become a substantial public health burden, necessitating the need for increased understanding of the prediction of outcomes. The majority of children who sustain a concussion recover well, within several weeks; however, a significant minority of children suffer from persistent symptoms that hamper return to school and play (Rose, McNally, & Heyer, 2016; Eisenberg, Meehan, & Mannix, 2014; Barlow et al., 2010). Furthermore, children who suffer persistent symptoms following a concussion are more likely to experience broad problems in social, physical, emotional, and academic functioning (Laliberté Durish, Brooks, & Yeates, 2018b; Novak et al., 2016; Grubenhoff et al., 2015; Tham et al., 2013, 2015) that can further impact return to baseline. Predicting the likelihood of adaptive versus poor recovery following concussion is crucial to enable proactive implementation of appropriate treatment recommendations in order to mitigate the downstream of effects related to poor recovery. However, prediction of outcomes of concussion has been an ongoing challenge faced by researchers and clinicians, particularly due, in part, to the significant role that non-injury factors play in accounting for the heterogeneity of outcomes.

A strong body of literature suggests a significant impact of psychosocial and environmental factors that impact individual recovery (Bernard et al., 2016; McNally et al., 2013; Yeates et al., 2012; Woodrome et al., 2011; Taylor et al., 2010). Such research is particularly focused on predicting poor outcomes among this population. However, mere focus on examining predictors of poor outcome narrows the lens of research to omit the majority of individuals who indeed recover well. Broadening the lens of research to examine factors that contribute to positive outcomes of concussion is necessary to better understand the greater population of children who sustain a concussion. Moreover, examining factors related to improved outcomes can guide intervention efforts towards harnessing such factors to promote wellness, rather than merely mitigate problems. As such, recent research has begun to examine the role of resiliency in predicting wellness following concussion (e.g., Laliberté Durish, Brooks, & Yeates, 2018a, 2019; Losoi et al., 2015a, 2015b, 2016). Typically studied in the context of psychosocial and environmental adversity, resilience research has provided a framework by which to better understand adaptive outcomes of physiological adversity, such as concussion. Exploration of protective factors that mitigate impacts of neurological insult is, however, not a novel undertaking. Indeed, the concepts of cognitive and brain reserve have been explored as factors that account for individual variability in outcome of neurological insult, in that individuals with greater levels of reserve have been found to better withstand functional impacts of neurological disease or injury (Stern, 2003; 2012; Satz, 1993). Few studies have examined the roles of cognitive reserve, brain reserve, or psychological resilience in the context of pediatric concussion. Moreover, no known study has examined the roles of all three factors in this population in a single model, nor examined how such factors are related to one another in this population.

This dissertation document comprises two separate, but related, studies. The first study is a scoping review of the literature examining the roles of cognitive reserve, brain reserve, and resilience in all severities of traumatic brain injury (TBI). The scoping review sought to describe the existing state of the research on reserve and resilience in TBI, as well as propose future areas of study in order to address gaps in the literature. The second study is an original research study examining the roles of cognitive reserve, brain reserve, and psychological resilience as predictors and moderators of group differences in trajectories of post-concussive symptoms in children with concussion, as compared to children with orthopaedic injury. The second study represents a subset of a larger parent study that broadly examines assessment and prognostic indicators of concussion and outcomes associated with concussion in children and youth (i.e., Advancing Concussion Assessment in Pediatrics; A-CAP; Yeates et al., 2017). Both studies represent novel contributions to the research examining reserve and resilience factors in pediatric concussion. The collective goal of this body of research is to examine factors that promote wellness in children with concussion, in an effort to guide future research efforts towards harnessing such factors to ultimately improve outcomes for children suffering from post-concussive symptoms.

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Study 1

Cognitive Reserve, Brain Reserve, and Psychological Resilience in Traumatic Brain Injury: A Scoping Review

Introduction

Traumatic Brain Injury

Traumatic brain injury (TBI), defined as the disruption of normal brain function caused by an injury sustained by external forces, affects over 2.8 million individuals in the United States, annually (CDC, 2019). Highest incidence rates are seen among older adults aged ≥ 75 years, young children aged 0-4 years, and young adults aged 15-24 years (CDC, 2019). TBI severity (i.e., mild, moderate, severe) is classified according to the extent of damage sustained to the brain. Severity is typically measured by quantifying level of consciousness (i.e., ocular, verbal, and motor response) using the Glasgow Coma Scale (GCS; Teasdale & Jennette, 1974), with mild TBI representing minor impairment of consciousness or absence of impaired consciousness (i.e., GCS = 13-15), and severe TBI representing significant impairment of consciousness (i.e., GCS ≤ 8). The term "concussion" is often used interchangeably with mild TBI and represents the mildest severity of TBI.

TBI is often associated with an array of physical, cognitive, and psychosocial sequelae. However, prediction of prognosis following a TBI is hampered by significant heterogeneity in individual outcomes (Lingsma et al., 2010). While more severe injuries, as evidenced by lower GCS scores and abnormalities identified on neuroimaging, are typically associated with worse outcomes (Olsson et al., 2013; Yeates et al., 2012; Lingsma et al., 2010; Taylor et al., 2010), extensive research has identified the significant role that non-injury factors play as contributors to the prediction of outcomes. Pre-morbid psychological factors, such as a history of learning problems, psychiatric problems, low self-esteem, or poor behavioural adjustment, have been found to be associated with worse outcome, regardless of injury severity (Catroppa et al., 2017; Yeates et al., 2012; Ponsford et al., 1999). Environmental variables such as lower socioeconomic status (SES) and problematic family functioning have also been linked to worse outcomes following TBI (Renaud et al., 2019; Taylor et al., 2010). Additionally, individual non-injury demographic factors, such as age at injury and sex, are also implicated in the prediction of outcome (Hukkelhoven et al., 2003; Andrews et al., 2002; Ono et al., 2001; Farace & Alves, 2000). As a contrast to the growing list of factors predictive of poor outcome following TBI, researchers have become increasingly interested in studying factors that promote wellness following TBI (e.g., Beauchamp et al., 2019). The concepts of "reserve" and "resilience" are two factors that have piqued the interest of researchers wishing to study protective factors found to be predictive of improved outcomes in a number of health-related problems, including TBI.

Reserve

The concept of reserve has been a major focus of research on protective factors involved in buffering the effects of neurological injury and disease. Reserve has been proposed as a mechanism by which to explain variability in functional outcomes following neurological insult (Stern 2002, 2003, 2009). Much of the knowledge on the topic of reserve originates from research in Alzheimer's disease. A study conducted by Katzman and colleagues (1988) was one of the first to identify a subgroup of Alzheimer's patients who, despite having high levels of pathology and neurodegeneration, were found to exhibit fewer functional deficits than their age and pathology-matched counterparts. Researchers have since been interested in understanding factors that contribute to reserve, as well as their applications to numerous other neurological and medical conditions, including TBI.

Theorists have developed two empirically-supported models of reserve, often conceptualized as active and passive reserve (Sole-Padulles et al., 2009; Stern, 2009; Satz, 1993). Active reserve refers to mechanisms that contribute to increased flexibility and efficiency of neural resources that enable an individual to actively compensate for neurological damage (Stern, 2009). The passive model of reserve posits that once neurological injury or disease surpasses an individual's capacity threshold, only then will the individual exhibit symptoms of brain damage (Sole-Padulles et al., 2009; Graves et al., 1996; Satz, 1993). That is, every individual has a pre-set, quantifiable capacity (e.g., brain size, number of neurons; Katzman, 1993; Mortimer et al., 1981) that determines how much damage can be sustained before functioning is compromised. The active model is generally studied in the context of cognitive reserve, whereas the passive model is generally studied in the context of brain reserve. Both models hypothesize that individuals with greater reserve (e.g., larger brain volume, greater cognitive resources) will exhibit fewer functional deficits compared to injury-matched counterparts with lower levels of reserve.

Cognitive Reserve

The cognitive reserve hypothesis posits that, rather than sole reliance on a static, physiological capacity, individuals can rely on alternate or more efficient brain networks to compensate for increased demand on the damaged brain (Stern, 2003). Cognitive reserve is not thought to represent a static trait, but rather a variable factor that can be influenced throughout the lifespan (Bigler & Stern, 2015; Lazarov et al., 2005; Richards & Sacker, 2003). Research supports numerous factors thought to contribute to cognitive reserve, including genetics, intelligence, occupational attainment, education level, rich social networks, and leisure activities (Bennett et al., 2006; Stern, 2003; Richards & Sacker, 2003; Scarmeas et al., 2001; Alexander et al., 1997; Stern et al., 1994; Stern et al., 1992). These factors are thought to represent opportunities for enrichment and efficiency of neural resources, thereby allowing for greater compensation or flexibility in order to optimize function in the context of brain damage. Neural compensation in the context of brain injury has been investigated through the use of functional magnetic resonance imaging (fMRI) methodologies, which have been utilized to measure recruitment of alternative brain regions, not otherwise typically activated in non-brain injured individuals, during cognitive task engagement (Ji et al., 2018; Steffener et al., 2011; Bartres-Faz et al., 2009). However, while existing evidence supports neural compensation as a potential mechanism of cognitive reserve, researchers note that compensation does not necessarily imply optimal functioning, as individuals who demonstrate greater compensation may do so at the cost of poorer behavioural performance (Stern, 2009; Grady et al., 1994). Researchers have therefore also investigated neural efficiency as another potential mechanism of cognitive reserve, and have demonstrated findings that provide support for greater flexibility and capacity of existing neural networks that enable preservation of cognitive function (Zarahn et al., 2007).

Measurement of cognitive reserve via indirect observation of neural compensation and/or efficiency through the use of neuroimaging techniques can be a costly undertaking. Therefore, researchers have often relied on measures of intelligence quotient (IQ), education, or occupational attainment as affordable and robust proxies of cognitive reserve (Stern, 2003; Alexander et al., 1997; Stern et al., 1992). Such proxies are thought to be representative of genetic and environmental factors that correlate with the enrichment of neuronal resources.

Brain Reserve

Brain reserve is hypothesized to account for individual differences in the expression of functional deficits due to brain pathology based on an individual's physiological capacity or threshold (Satz, 1993). This passive model of reserve posits that larger brain size accounts for individual variability in neurological functioning post-insult due to a greater capacity to withstand damage. The concept of brain reserve is based on a quantifiable measure of brain capacity, and is therefore often assessed through the measurement of brain volume, head circumference as an indirect measure of brain volume, or neuronal count. Obvious logistic challenges are associated with use of neuronal count as a method of measuring brain reserve, and head circumference is thought to be a less robust proxy of brain reserve given variability in differences between brain size and head circumference, particularly in the context of brain injury (i.e., brain atrophy would result in lower brain volume but not cranial shrinkage; Bigler, Johnson, & Blatter, 1999).

Brain reserve and cognitive reserve are not thought to be independent constructs, as enriching environments, measured as proxies of cognitive reserve, can contribute to increased synaptic density and neuronal growth (Brown et al., 2003; Nilsson et al., 1999), and thus, increased brain reserve. Although theoretically overlapping, these constructs are nonetheless thought to contribute differentially to outcomes of neuropathology, as correlations among the constructs are not so high as to suggest the two are one in the same (Wickett et al., 1994). Given that cognitive and brain reserve account for significant variability in outcome of neurological injury or disease, they are therefore important factors to consider in the context of understanding heterogeneity of outcomes in TBI.

Psychological Resilience

Resilience, broadly defined, refers to “positive adaptation in the context of significant challenges, variously referring to the capacity for, processes of, or outcomes of successful life-course development during or following exposure to potentially life-altering experiences” (Masten, 2009). Various factors have been implicated in the contribution to one’s ability to demonstrate resilience in the face of adversity. Such factors include personal attributes, family factors, and broader social and community environments (Luthar, 2006). While external factors, such as family and societal factors, are paramount in their contribution to the broad construct of resilience, many external factors that impact resilience are limited in their feasibility to be quantitatively measured or modified through intervention. Thus, researchers have focused on individual resilience factors that can be quantified, and potentially modified, such as psychological aspects of resilience, to better understand mechanisms of successful adaptation following adversity. Psychological resilience specifically refers to a group of personal characteristics that, when harboured, enable positive adaptation to stressful, adverse experiences. Such characteristics include personal competence, high standards, tenacity, trust in one's instincts, tolerance of negative affect, positive acceptance of change, security in relationships, a sense of control, and spiritual motivation (Connor & Davison, 2003). While resilience can be impacted by and demonstrated at a familial and societal level, for the purposes of the current review, resilience hereby refers to individual, psychological resilience.

Historically, the concept of resilience has been examined in the context of childhood maltreatment and adverse rearing environments (e.g., Werner, 1997; Werner & Smith, 1992; Anthony, 1974). Such studies have focused on identifying and understanding children who, despite undergoing experiences of significant trauma, demonstrate high levels of functioning and adaptability. However, increasingly, resilience has been examined in the context of physical disease and injury, including TBI, to better understand factors that promote improved outcomes. In the context of physical disease, research has indicated key theoretical facets related to the definition of resilience, including the necessary prerequisite of the presence of an adverse experience (i.e., injury or disease), the ability to maintain healthy functioning despite adversity, and the view of resilience as a dynamic concept rather than a fixed trait (Johnston et al., 2015). The general consensus among modern researchers is that psychological resilience is a dynamic, state-like construct, which has implications for intervention. A study conducted by Steinhardt and Dolbier (2008) reported a significant increase in resilience among a group of college students who underwent a resilience training program, compared to a control group who did not complete the program, thus supporting the potential modifiability of resilience. Identifying modifiable individual factors related to outcomes in TBI, such as resilience, is important for guiding research towards interventions aimed at improved outcomes.

Objectives

The current scoping review aimed to collate published research examining the roles of cognitive and brain reserve, as well as psychological resilience, in the context of TBI. Importantly, while collation of the more extensive literature regarding the roles of reserve and resilience in the context of other forms of acquired brain injury (i.e., stroke, brain tumor) would offer a more thorough understanding of the broader topic, the current review sought to focus specifically within a TBI population. The scoping review had the following aims: (1) examine the constructs measured as proxies of reserve and resilience, as well as which tools are used to measure such proxies, (2) explore construct validity and mechanisms of reserve and resilience in the context of TBI, including the stability of reserve and resilience and their amenability to modification through intervention, (3) describe the relationships among reserve and resilience in the context of TBI, and (4) identify outcomes of TBI predicted by reserve and resilience.

Methods

The procedure for the current scoping review adhered to Arksey and O'Malley's (2005) methodological framework for scoping reviews. As per this framework, the review included the following steps: (1) establish the research question, (2) perform a literature search to identify relevant studies, (3) select studies applicable to the research question, (4) extract data from included studies into a chart, and (5) collate, summarize, and report the results (see Figure 1). MEDLINE Ovid and PsycINFO Ovid databases were utilized to conduct the literature search. The search criteria included all research articles from inception to April 24, 2020, limited to human subjects and English language. The keyword search included relevant expanded subject headings resulting in the following search terms: (traumatic brain injury OR brain concussion OR concussion) AND ((resilience, psychological OR resilience) OR (cognitive reserve OR brain reserve)).

The original database searches generated a total of 257 articles. Titles and abstracts were screened with the following inclusion criteria: (i) participants (all ages) with a diagnosis of TBI (all severities), (ii) examines cognitive reserve (broadly defined), brain reserve (broadly defined), and/or resilience (broadly defined), with specific reference to these constructs. The following exclusion criteria were applied: (i) non-empirical studies (e.g., reviews, case studies, editorials), (ii) "grey" literature (e.g., conference abstracts, dissertations), (iii) non-TBI samples (e.g., acquired brain injury from other causes; stroke, brain tumor), (iv) no explicit reference to reserve or resilience, (v) does not examine reserve or resilience with specific reference to the individual with TBI (i.e., reserve/resilience measured in the context of family members/caregivers of individuals with TBI), and (vi) animal studies. Following title/abstract screen and removal of duplicates (38), a total of 69 articles were included for full-text review. Twenty-two articles were excluded during full-text review for not meeting inclusion criteria (e.g., reserve/resilience measured in the context of a family member/caregiver; article deemed "grey" literature; reserve/resilience not quantitatively measured; sample not specific to TBI). Thus, a total of 47 articles met inclusion criteria for the current scoping review. The scoping review was conducted in accordance with the PRISMA extension for scoping reviews (Tricco et al., 2018).

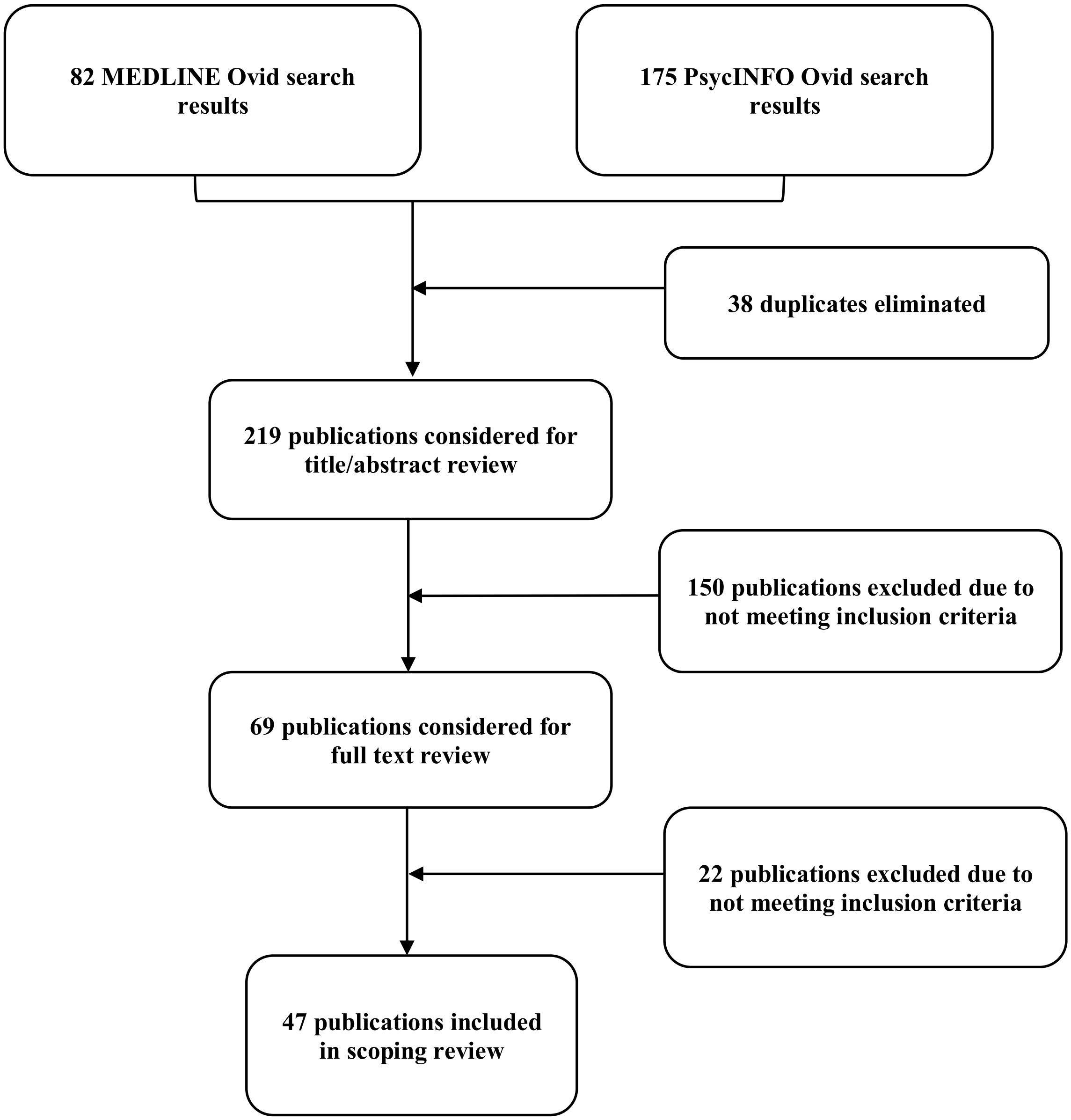

Figure 1. Literature review process

Results

Study Characteristics

An overview of the study aims, design, sample, measured variables, and relevant findings of each article included in the review (*n* = 47) are outlined in Table 1. Study dates ranged from

2003 to 2020. Studies were conducted in the United States of America (28), Canada (6), Finland (3), Australia (2), Israel (2), Sweden (2), Norway (2), Lebanon (1), and Italy (1). All publications included were original research studies, of which 30 recruited participants retrospectively (27 cross-sectional design, 1 longitudinal design, 1 randomized-controlled trial, 2 mixed method design), 16 employed a prospective, longitudinal design, and 1 study employed a prospective cross-sectional design. Thirty-eight studies included an adult sample (>18 years of age), 7 studies included a pediatric sample (<18 years of age), and 2 studies included both adolescents (≥16 years) and adults. TBI severity ranged from mild to severe. The majority of studies grouped together multiple severities of TBI (i.e., mild, complicated mild, moderate, severe), with 22 studies examining severity-specific effects or group differences among severity groups. Of the 9 studies of cognitive reserve that examined severity-specific effects, 4 were focused on mild TBI. Of the resilience studies that examined injury group differences (i.e., 14 studies), 13 were focused on mild TBI. Eighteen studies included non-TBI comparison groups (5 included healthy controls, 10 included orthopaedic injury controls, 3 included non-TBI military service member/veteran controls, and 1 included a post-anoxic encephalopathy comparison group). Of the studies included in the review, 17 examined cognitive reserve, 1 examined both brain and cognitive reserve, and 29 examined resilience. No studies focused solely on brain reserve.

Table 1
Overview of studies included in scoping review.

Author, Year; Country	Aims	Design	Sample	Measured Variables	Relevant Findings*
			Cognitive Reserve		
Donders & Kim, 2019; USA	Examined cognitive reserved as a moderator of cognitive outcomes following pediatric TBI.	Cross-sectional design. Data retrieved retrospectively from a clinical database of patients who underwent neuropsychological evaluations at an outpatient clinic between 2015 to 2017. Data from the TBI group were compared with data from a demographically matched WISC-V standardization sample.	Children (*N*=120), ages 6- to 16-years, with a history of TBI (*n*=60): -Mild TBI *n*=39; 49% female; age *M*=13.7(2.4), TSI (days) *M*=152.5(77.8) -Moderate-to-severe TBI *n*=21; 29% female; age *M*=12.5(6.5); TSI (days) *M*=116.8(77.9) Demographically matched controls *n*=60; 42% female; age *M*=13.3(2.6)	-Cognitive reserve: highest parental education level (high parental education = ≥ 13 years, low parental education = ≤ 12 years) -Cognitive outcomes: WISC-V FSIQ, Verbal Comprehension Index (VCI), Visual Spatial Index (VSI), Fluid Reasoning Index (FRI), Working Memory Index (WMI), Processing Speed Index (PSI)	-High parent education was associated with better performance on Verbal Comprehension, Visual Spatial, and Fluid Reasoning Indices. -Significant interaction between group (TBI vs. control) and cognitive reserve on FSIQ, VCI, and VSI, with group differences in scores (TBI performing worse than controls) more pronounced among those with low parental education vs. high parental education. -Authors concluded that cognitive reserve moderated some (but not all) cognitive outcomes of pediatric TBI.
Donders & Stout, 2019; USA	Examined cognitive reserve as a predictor of cognitive functioning among individuals with TBI.	Cross-sectional design. Data retrieved retrospectively from a database of patients who underwent neuropsychological evaluations at a rehabilitation facility between 2015 to 2017.	Adults (*N*=121) with TBI (uncomplicated mild TBI *n*=75, complicated mild to severe TBI *n*=46) Age *M*=41.1(15.0); TSI (days) *M*=182.5(86.6), range=1-12 months	-Cognitive reserve: TOPF + demographic variables (geographic region, gender, race/ethnicity, education, occupation) -Cognitive outcomes: WAIS-IV VCI, PRI, WMI, PSI -Depressive symptoms: PHQ-9	-Greater cognitive reserve was a significant predictor of higher VCI, PRI, WMI, and PSI scores. -Injury severity was a significant predictor of PSI scores, over and above cognitive reserve.
Fay et al., 2010; USA	Examined the moderating effect of cognitive reserve on the relationship between mild TBI and PCS.	Prospective longitudinal design. Children recruited from an emergency department following presentation with a mild TBI or OI. Assessment of PCS and cognitive reserve was completed within 3 weeks of injury. Follow-up PCS assessments were completed at 1-, 3-,	Children (*N*=281), ages 8- to 15-years, with: -Complicated mild TBI: *n*=32; age *M*=12.2(1.9) -Uncomplicated mild TBI: *n*=150; age *M* = 12.0(2.3) -OI: *n*=99; age *M* = 11.8(2.2).	-Cognitive reserve: Cognitive ability represented by a single composite score derived from the following measures: WASI; WRAT-3; CVLT-C; VMI; CANTAB Pattern Recognition Memory, Stockings of Cambridge, Spatial Working Memory -PCS: PCS-I; HBI	-At 3-months post-injury, children in all groups with higher cognitive ability demonstrated fewer parent-rated overall and somatic PCS, as well as fewer self-reported cognitive PCS. Further, they demonstrated relatively few parent-rated cognitive and self-reported overall PCS across time. -Children with lower cognitive ability in the complicated mild TBI group demonstrated a rapid increase in parent-rated cognitive PCS across the first 3-

		and 12-months post-injury.			months post-injury, compared to children with lower cognitive ability in the other groups. -Children with lower cognitive ability in the complicated mild TBI group demonstrated greater self-reported overall PCS at the initial assessment, compared to children in the same group with higher cognitive ability; although, this difference was no longer present by 3 months post-injury. -Children with lower cognitive ability in the uncomplicated mild TBI group demonstrated greater self-reported overall PCS at the initial and 1-month assessment, compared to children with lower cognitive ability in the OI group; although, this difference was no longer present at 3 months post-injury. -Authors conclude that children with higher cognitive ability (i.e., greater cognitive reserve) may be more protected against the effects of complicated mild TBI, while those with less reserve demonstrate greater vulnerability to the development of PCS immediately after and up to 3-months post-injury.
Fraser et al., 2019; Australia	Examined the association of injury severity and cognitive reserve to cognitive functioning 2- and 5-years post-TBI.	Prospective longitudinal design. TBI participants completed assessments after emergence from PTA, as well as follow-up assessments between 2- and 5-years post-injury (*M*=3.7 years). Healthy controls completed an assessment at a single time point.	Adults (*N*=109) with complicated mild, moderate, or severe TBI (*n*=109; 41% severe) and healthy matched controls (*n*=63). TBI: Age at injury *M*=44.6(16.7), range=20-85 years; 29% female	-Cognitive reserve (estimated premorbid IQ): NART -Cognitive outcomes: WAIS-III Digit Symbol-Coding; RAVLT; TMT	-Higher estimated premorbid IQ predicted better cognitive performance at the initial assessment, as well as greater cognitive recovery at follow-up (even after accounting for initial performance). -Authors conclude findings support an active model of reserve.

Fuentes, McKay, & Hay, 2010; Canada	Examined the relationship among neuropsychological performance and cognitive reserve in children with TBI with the goal of (a) examining whether this observed relationship in adult TBI is also seen in a pediatric TBI population, and (b) if well-recognized indicators of cognitive reserve are valid indicators in pediatric populations.	Cross-sectional design. Children with TBI who were referred to a neuropsychology service of a non-acute inpatient/day patient neurorehabilitation hospital were assessed within 3- to 6-months post-injury.	Children (*N*=52), ages 6-16 years, with TBI (70% moderate-to-severe TBI, 30% mild/complicated mild TBI). Age *M* = 11.8(3.1); 35% female	-Cognitive reserve: WIAT-II Word Reading; WISC-IV Vocabulary. -Neuropsychological performance: TEA-Ch; WISC-IV PSI; CVLT-C; RCFT; WCST; CCT	-Neither measure of cognitive reserve was significantly correlated with the majority of neuropsychological measures, with exception of the WIAT-II Word Reading correlation with divided attention measures of the TEA-Ch, and the WISC-IV Vocabulary correlation with verbal learning on the CVLT-C. -Authors conclude that the moderating effect of cognitive reserve on neuropsychological outcome in adult TBI may not apply to a pediatric TBI population. As well, they concluded that the study provides evidence against the validity of traditional cognitive reserve proxies of reading ability/vocabulary when applied to a pediatric population.
Krch et al., 2019; USA	Examined the moderating effect of cognitive reserve (CR) on cognitive outcomes of TBI.	Cross-sectional design. Cognitive and DTI data were collected from participants approximately 1-year post-injury (*M*=8.5 years).	Adults (*N*=61) with complicated mild to severe TBI separated in to 2 groups: -High CR (i.e., WTAR standard score < 97; *n*=21) -Low CR reserve (i.e., WTAR standard score > 111; *n*=21) Overall Sample: Age *M*=41.2(12.8); Age at injury *M*=33.1(13.5); 25% female	-Cognitive reserve: WTAR -Cognitive outcomes: CVLT-II; WMS-IV; BVMT-R; WAIS-IV Digit Span, Symbol Search; BTA; Stroop Color-Word; Color Trails; phonemic FAS and semantic fluency; Symbol Digit Modalities Test; Letter and Pattern Comparison; Word Reading	-WTAR scores were unrelated to time since injury or neuropathology (measured by fractional anisotropy; FA). -The high CR group performed significantly better than the low CR group in contextualized memory and executive functioning. -CR moderated the relationship between neuropathology and memory performance. At higher FA (lower levels of pathology), individuals with higher CR had better memory performance than those with low CR. This benefit diminished as FA decreased. -Those with complicated mild/moderate TBI and high CR had better memory performance than those with low CR, whereas no CR group differences were present among those with severe TBI.
Leary et al., 2018; USA	Investigated the relationship among cognitive reserve factors (estimated	Cross-sectional design. Participants were selected from a pool of individuals participating	Adults (*N*=100) with TBI 68% mild, 25% moderate, 17% severe	-Cognitive reserve: ToPF; years of education; pre-injury occupational attainment (2010	-Significant positive correlations among (1) estimated premorbid IQ and the following neuropsychological measures: BCT, CVLT, Grooved Pegboard, Trail

	premorbid IQ, years of education, occupational attainment) and post-injury functional and neuropsychological outcomes following TBI.	in a longitudinal parent study. Participants were selected if they had available data 1-year postinjury or later, as well as valid neuropsychological testing. Data from the most recent assessment time point was utilized.	Age *M*=46.6(16.4); 63% male; TSI (years) *M*=2.5(1.2)	Standard Occupational Classification System) -Neuropsychological outcomes: BCT; CVLT; FTT; Grooved Pegboard; Trail Making Test; WAIS-IV -Depressive symptoms: BDI -Functional outcomes: GOS-E	Making Test B, WAIS-IV Working Memory, WAIS-IV Processing Speed; (2) years of education and the following neuropsychological measures: CVLT, WAIS-IV Working Memory, WAIS-IV Processing Speed. -No differences in neuropsychological outcomes between occupational attainment levels. -No significant relationships among any cognitive reserve factors and functional outcomes. -No significant relationship among cognitive reserve factors and outcome measures in the severe TBI subgroup. -Authors conclude that results support the positive relationship between cognitive reserve factors and neuropsychological outcomes in individuals with TBI.
Levi et al., 2013; Israel	Evaluated several models hypothesized to represent cognitive reserve in TBI.	Cross-sectional design. Structural equation modelling was employed to examined whether three cognitive reserve components (estimated premorbid IQ, engagement in leisure activities, socioeconomic status (SES)) reflect a single construct or separate cognitive reserve domains. Data were collected through in-person interviews, neuropsychological assessments, medical records, and completion of questionnaires.	Adults (*N*=89) with moderate-to-severe TBI. Age at injury *M*=26.1(8.2), range 18-58; age at testing *M*=40.3(13.6), range 19-73; 90% male TSI (years) *M*=14.3(14.2), range 1-53; GCS *M*=5.7(3.1)	-Premorbid SES: Parents' occupation; sibling number; household income; self-reported SES -Estimated premorbid IQ: WAIS-III Information, Vocabulary, Matrix Reasoning -Premorbid leisure activity (cognitive, social, physical): Modified adaptation of Lifetime of Experience Questionnaire	-Significant covariance was found between SES and leisure activity, and between SES and IQ. -A three-factor model (premorbid IQ, SES, leisure activity represented as three separate latent variables underlying cognitive reserve) fit the data best in comparison to two-factor models (SES/leisure activity and premorbid IQ; SES/IQ and leisure activity), and a one-factor model (all variables representing one single latent variable underlying cognitive reserve). -Authors conclude that results indicate that cognitive reserve is not a unitary structure, but rather a multidimensional one with at least three components.

Luis, Vanderploeg, & Curtiss, 2003; USA	Examined (1) the presence of persistent postconcussion symptom complex (PPCSC) among a non-referred, community dwelling sample of male veterans; (2) the contribution of pre-existing psychiatric difficulties, demographic and social support variables, and history of an accidental injurious event to the presence of PPCSC in the sample; (3) whether the influence of such variables differed between mild TBI and non-TBI samples.	Cross-sectional design. Study utilized data collected in the mid-1980s as part of a larger parent study. Participants completed a 3-day evaluation involving extensive medical, psychological, and neuropsychological examinations.	*N*=3957 male US Army Veterans who served during the Vietnam Era. Participants were divided into four groups: -No MVA/no HI: i.e., those who have not experienced injury due to a motor vehicle accident (MVA) or a head injury (HI) since military discharge; *n*=2937, age *M*=38.5(2.52) -MVA/no HI: i.e., injury due to MVA without HI since military discharge; *n*=488, age *M*=38.27(2.54) -HI/no LOC: i.e., HI since military discharge with no loss of consciousness (LOC); *n*=323, age *M*=38(2.58) - HI/LOC: i.e., HI since military discharge with LOC; *n*=209, age *M*=37.86(2.51) TSI: Evaluations were conducted approximately 16 years post-military discharge; MVA and/or HI estimated to have occurred on average 8 years prior to the evaluation. Data on severity of HI was not available, although no HI participants required overnight hospitalization due to the injuries sustained.	-PPCSC: Semi-structured interview and responses to items on the MMPI; criteria for ICD-10/DSM-IV Postconcussion Syndrome were used as a guideline to determine if participants met criteria for PPCSC (although, PPCSC did not require the presence of a documented head injury, neuropsychological symptoms, or preoccupation with symptoms). -Demographic variables: age, education, race, level of intellectual ability at enlistment (i.e., cognitive reserve; defined as performance on the General Technical Test) -Early life psychiatric difficulties/satisfaction with social support: DIS-III-A	-Among the overall HI sample, presence of PPCSC was more likely in individuals of lower premorbid intelligence. -HI participants with lower levels of intelligence and a history of LOC had the highest rate of PPCSC when compared to the HI/no LOC group. This group difference disappears among individuals with average to high intelligence (i.e., moderating effect of premorbid intelligence). -HI participants with average intelligence demonstrated a differential benefit from good social support and an enhanced vulnerability to PPCSC with poor social support; however, participants with below or above average premorbid intelligence demonstrate a more linear effect of social support on PPCSC (i.e., higher rates of PPCSC among those with lower social support). -Among the non-HI sample, the presence of PPCSC was more likely among individuals of lower premorbid intelligence and lower perceived social support.
Mahdavi, Hasper, & Donders, 2019; USA	Examined whether sluggish cognitive tempo (SCT) was predictive of processing speed among children with	Cross-sectional design. Data were drawn from a clinical database of outpatient neuropsychological assessments of patients	Children (*N*=50) with a history of uncomplicated mild (*n*=37) or moderate-to-severe (*n*=13) TBI.	-Cognitive reserve: Parental education -SCT: CBCL parent-report SCT scale -Processing speed : WISC-IV PSI	-Participants with moderate-to-severe TBI had significantly lower CR (parental education) than those with mild TBI. -CR was not correlated with processing speed or SCT.

	TBI while accounting for injury factors and cognitive reserve.	who sustained mild, moderate, or severe TBI. Assessments were conducted within 1-12 months post-injury.	Age *M*=13.42(2.95), range=6-16 years; 42% female; TSI (days) *M*=152.28(64.97)		-CR did not mediate the relationship between injury and neuropsychological outcome.
Menardi et al., 2020; Italy	Examined the role of cognitive reserve in patients with a history of severe post-anoxic encephalopathy (PAE) or severe TBI.	Cross-sectional design. Data were collected retrospectively from medical charts of patients hospitalized for PAE or TBI. Participants were contacted and completed a questionnaire of cognitive reserve via telephone.	Adults (*N*=50) diagnosed with PAE (*n*=20) or TBI (*n*=30) TBI: Age *M*=47.9(12.24); 23% female	-Cognitive reserve: CRIq -Functional outcome: LCF scale; DRS; FIM; BI	-Patients in both groups with higher CR were more likely to show preserved pupillary reflex and somatosensory evoked potentials immediately after injury, as well as shorter periods of hospitalization, reduced risk of seizures, and lower GCS scores.
Oldenburg et al., 2016; Sweden	Investigated the associations among cognitive performance, PCS, and cognitive reserve in a sample of patients with mild TBI.	Prospective longitudinal design. Subset of a larger parent study. Participants recruited from an emergency department <24 hours following sustainment of a mild TBI. Healthy (non-injured) control group recruited through local advertising. Self-reported PCS ratings were collected 1-day following injury, a psychiatric interview was conducted 7-days post-injury, and a follow-up assessment involving PCS symptom ratings and a neuropsychological assessment was completed 3-months post-injury.	Adults (*N*=137) with mild TBI who reported 3 or more PCS at 3-months post-injury (i.e., "PCS group"; *n*=34; age *M* =37.2(14.5); 44% male), or less than 3 PCS at 3-months post-injury (i.e., "recovered group"; *n*=68; age *M*=37.1(15.4); 68% male) and healthy non-injured controls (*n*=35; age *M*=39(14.9); 49% male). Note: Only the mild TBI groups completed neuropsychological measures. Of those, only 82 were included in the final analyses. Thus, results reported herein pertain only to the mild TBI group.	-Cognitive reserve: Premorbid IQ (WAIS-R Information subtest); education level (International Standard Classification of Educational Degrees); occupational skill level (International Standard Classification of Occupation). -PCS: RPCSQ. -Neuropsychological functioning: Processing speed/information processing/attention/psychomotor speed (PASAT, WAIS-R Digit Symbol); Verbal learning/memory (Selective Reminding Test); Cognitive flexibility (Stroop Colour and Word Test); Working memory (WAIS-R Digit Span, WAIS-R NI Block Span); Visual scanning/graphomotor speed/mental flexibility (Trail	-The PCS group demonstrated significantly lower premorbid IQ than the recovered group and the control group. -All three measures of cognitive reserve demonstrated a significant negative relationship with PCS at 3-months post-injury. -In a logistic regression model, pre-morbid IQ was the sole significant predictor of the presence of PCS at 3-months post-injury.

				Making Test); Performance validity (Reliable Digit Span)	
Ropacki & Elias, 2003; USA	Examined the effects of premorbid history variables and head injury on cognitive reserve.	Cross-sectional design. Participants were referred for a neuropsychological assessment following a traumatic brain injury. Participants completed neuropsychological evaluations after their transition to inpatient rehabilitation or as soon as possible following hospital discharge prior to beginning outpatient rehabilitation.	Adults (*N*=26) with TBI of varying severities. Participants were divided into two groups based on premorbid history: -TBI+: Positive for premorbid history of alcoholism, drug abuse, psychiatric history, and/or previous neurological insult (*n* = 9; 7 mild, 1 moderate, 1 severe; age *M*=62.11(25.03)). -TBI-: Negative for premorbid history of variables (*n* = 17; 7 mild, 2 moderate, 8 severe; age *M*=42.94(32.57)) Overall sample 54% male	-Cognitive reserve: Premorbid IQ (OPIE); education level; occupational attainment -Neuropsychological functioning: WAIS-R, WMS/WMS-R, Stroop Colour-Word Test, Trail Making Test	-The groups did not significantly differ on measures of premorbid IQ. -The TBI+ group, who sustained less severe injuries compared to the TBI- group, demonstrated greater differences in premorbid performance IQ (as measured by the OPIE) vs. post-injury performance IQ (as measured by the WAIS-R), compared to the TBI- group. -The TBI+ group demonstrated a greater post-injury verbal IQ/performance IQ discrepancy, compared to the TBI- group. -Group differences were also present on Trail Making and Stroop Colour-Word tests. -The authors conclude that results support the notion that individuals with a premorbid history of alcoholism, drug abuse, psychiatric history, and/or previous neurological insult have lower cognitive reserve and therefore are more sensitive to the cognitive effects of head injury, compared to individuals without such history.
Schiebel et al., 2009; USA	Examined (1) the relationship between acute severity of TBI (measured by GCS scores) and brain activation during performance on a stimulus-response compatibility fMRI task, and (2) the contribution of age, education, and preinjury IQ among	Cross-sectional design. Participants were recruited from trauma centres around the time of injury. fMRI was completed once PTA, physical injuries, and pain that could interfere with scanning procedures had resolved. Additional measures were completed on the same day as the fMRI.	Adults (*N*=40) with moderate TBI (n=9; age at injury *M*=46.32(7.29); TSI (years) *M*=0.31(0.06)), severe TBI (*n*=8; age at injury *M*=22.46(3.99); TSI (years) *M*=0.30(0.04)), very severe TBI (*n*=13; age at injury *M*=24.12(7.04); TSI (years) *M*=0.34(0.10)), and OI (*n*=10; age at injury *M*=30.79(10.46); TSI (years) *M*=0.38(0.24)).	-Functional outcome: GOS-E -Depressive symptoms: CES-D	-Groups did not differ on education, estimated premorbid IQ, or TSI, however, they differed on age (moderate TBI older than OI). -Higher education levels were associated with greater activation within a large, left-sided cluster that included the cingulate gyrus, and areas of the frontal and parietal lobes (authors conclude this relationship may indicate that education facilitates the ability of individuals with neuropathology to engage a left-sided neural network for verbal guidance or

	individuals who sustained moderate-to-severe TBI.				mediation while performing the task as a method of compensation). -Association between lower estimated premorbid IQ and higher levels of brain activation within midline cerebral structures (i.e., greater compensation due to lower reserve).
Stenberg et al., 2020; Norway	Investigated cognitive reserve as a moderator of differences in cognition among patients with and without mTBI at 2-weeks and 3-months post-injury.	Prospective longitudinal design. Participants were recruited from a trauma centre, emergency department, and the community. mTBI and OI participants completed cognitive measures at 2-weeks and 3-months post-injury. Healthy controls completed cognitive measures at two time points, 3 months apart.	Adolescents and adults (*N*=310) with mTBI (*n*=160), OI (*n*=71), and healthy controls (*n*=79) (age sex, and education matched) Overall sample age range=16-59 years mTBI: Age *M*=32.8(13.2); 34% female	-Cognitive reserve: WASI Vocabulary -Cognitive outcomes: WAIS-IV Coding, Symbol Search; AVLT; Verbal Fluency -PCS: British Columbia PCSI	-Higher cognitive reserve was associated with higher cognitive scores in all groups across both time points. This effect was significantly larger for the mTBI group vs. HC group. -Lower cognitive reserve was associated with the presence of PCS. -Cognitive reserve did not moderate rate of cognitive recovery.
Steward et al., 2018; USA	Examined cognitive reserve (as measured by estimated premorbid IQ) as a predictor of cognitive outcome at 1-month post-injury and rate of recovery over the first year post-injury in TBI and healthy controls.	Prospective longitudinal design. Participants were recruited from hospitals. Initial assessment was completed within 2- to 6-weeks post-injury. Follow-up assessments were completed at 6- and 12-months post-injury. Healthy controls were recruited from local advertisements. Participants completed a battery of neuropsychological measures at each visit.	Adults (*N*=175) with TBI (mild: *n*=28, age *M*=35.4(12.4), 54% male, GCS *M*=14.6(0.8); complicated mild: *n*=24, age *M*=45.5(18.4), 54% male, GCS *M*=14.7(0.6); moderate-to-severe: *n*=57, age *M*=35.5(14.8), 79% male, GCS *M*=5.8(3)) and healthy demographically matched controls (*n*=66, age *M*=35.4(14.4), 61% male)	-Cognitive reserve (estimated premorbid IQ): WTAR -Neuropsychological functioning: Processing speed/executive function (Trail Making; WAIS-III Digit Symbol Coding, Symbol Search); Verbal fluency; Memory (CVLT-II; WMS-III).	-The moderate-to-severe TBI group had significantly lower estimated premorbid IQ compared to other groups. -Higher cognitive reserve (estimated premorbid IQ) was associated with better cognitive performance in all domains, regardless of injury status. -Authors conclude that the study does not provide evidence that cognitive reserve reaches a brain damage threshold. -Cognitive reserve not found to impact the rate of cognitive adaptation following TBI. -Authors conclude that findings provide support for a neural reserve model of cognitive reserve (i.e., differences in efficiency and capacity of cognitive processing that protect networks from

					disruption following injury), but not a compensation model of cognitive reserve (i.e., differences in capability of existing brain networks to adapt and reorganize following injury) in a TBI population.
Wright et al., 2016; USA	Examined whether concussion frequency, severity, and timeframe, as well as cognitive reserve, are predictive of cognitive outcomes in retired American professional football players.	Cross-sectional design. Subset of a larger parent study. Participants recruited from existing research databases at a study centre. Participants completed a neuropsychological assessment. Additional demographic and history data was collected via questionnaires and interviews.	Retired professional football players (*N*=40) with a history of sports-related concussion during professional football tenure. Age: *M*=46.38(10.75)	-Cognitive reserve (premorbid IQ): American National Adult Reading Test (estimated verbal IQ); occupational attainment; academic achievement -Neuropsychological functioning (scores combined to produce a global cognition T-score): Verbal memory (CVLT-II); Visual memory (RCFT); Attention/processing speed/executive functioning (Symbol Digit Modalities; Trail Making Test); Verbal Fluency Test -Mood: HADS -Other variables of interest (collected via interview and questionnaires): demographics, concussion history, game play, steroid use	-Cognitive reserve did not correlate with depression scores or steroid use. -Cognitive reserve was significantly associated with body mass index (BMI). -Authors conclude that cognitive reserve and concussive history can be considered together to create an index that is predictive of cognitive outcomes among athletes with history of concussion. Further, individuals with greater cognitive reserve may be protected against negative effects of concussion frequency and/or severity over time than those with lower cognitive reserve.
			Brain Reserve		
Kesler et al., 2003; USA[1]	Examined the threshold model of cognitive reserve in TBI by analysing premorbid cognitive data, total intracranial volume (TICV), and post-injury brain morphology (ventricle-to-brain ratio; measure of cerebral atrophy).	Cross-sectional design. Participants were recruited from an existing research database. School records of pre-injury standardized testing scores were obtained for each of the participants. Data from magnetic resonance imaging (MRI) and cognitive	Adolescents (>16 years of age) and adults (*N*=25) with a history of TBI. Participants divided into two groups based on post-injury IQ: -High IQ: FSIQ ≥ 90; *M*=101(7.9) -Low IQ: FSIQ < 90; *M*=76(11.4))	-Brain reserve: TICV -Cognitive reserve: School records of standardized testing administered pre-injury (American College Testing Program, Stanford Binet, Differential Aptitude Test, Stanford Achievement Test, General Aptitude Test Battery, Armed Services Vocational Aptitude Battery)	-Post-injury IQ scores were significantly positively correlated with TICV, regardless of injury severity. -Participants in the "Low IQ" group demonstrated a greater IQ change score (negative change; created by calculating the difference between pre-injury IQ and post-injury IQ), compared to participants in the "High IQ" group, even though groups did not differ in terms of pre-injury IQ (however, the "High IQ" group

		testing were obtained from participants' enrollment in a previous study	GCS *M*=7.5(3.4), range=3-14; TSI > 6 months Age *M*=26.16(8.8), range = 16-42 years; 52% male.	used as a measure of pre-injury IQ -Post-injury IQ: WAIS-R	had a significantly higher education level). -Pre/post-injury IQ change was significantly greater for participants with lower TICV. -Education level was a significant predictor of post-injury IQ (positive correlation). -Pre-injury IQ was not significantly correlated with post-injury IQ or TICV. -Education and TICV were not significantly correlated. -Authors conclude that results of the study provide support for the passive model of cognitive reserve as a buffer against cognitive effects of TBI.
			Resilience		
Arbour et al., 2017; Canada	Examined the contribution of age to functional recovery and resilience following moderate-to-severe TBI.	Parallel mixed methods design. Participants completed questionnaires assessing resilience and depression, as well as engaged in open-ended and semi-structured interviews which were qualitatively analysed to abstract themes of resilience narratives.	Adults (*N*=13*) with moderate and severe TBI. Participants were divided into two groups according to age: 1. Young (18-44 years) *n*=8; 75% male; 38% moderate TBI; TSI (months) *M*=18(4) 2. Middle-aged (45-64 years) *n*=5; 80% male; 40% moderate TBI; TSI (months) *M*=20(4). *Resilience assessment data were only available for a portion of the overall study sample, reported herein. The overall study sample (*N*=144) included *n*=97 in the Young group (35% moderate TBI) and *n*=47 in the Middle-aged group (51% moderate TBI).	-Resilience: CD-RISC; qualitative narrative; semi-structured interview with open-ended questions. -Functional recovery: GOS-E -Depressive symptoms: BDI-II	-Greater resilience was significantly associated with fewer depressive symptoms in the overall resilience-measured sample. -Resilience narratives from the participants generated the following themes: attributing meaning to the TBI; creating a new support system; redefining roles and responsibilities; learning to live with chronic deficits; finding comfort in comparison; adjusting to having time on their hands; realizing their own resilience potential; adapting to being a changed person.
Donnelly et al., 2019; Lebanon	Evaluated the acceptability,	Mixed methods cohort study.	Adults (*N* = 857) with a history of TBI (*n* = 705; 46% mild,	-Resilience: TBI-QOL	-Significant improvements in pre-to post-intervention resilience scores, even after

	feasibility, and effectiveness of the LoveYourBrain Yoga program among adults with a history of TBI and caregivers of individuals with TBI.	Pre-/post-intervention quantitative and qualitative data were collected from individuals who participated in the program.	26% moderate, 28% severe) and caregivers of individuals with TBI (*n* =152).* TBI: Age *M*=43(12.8), range =15-70 years; 75% female; TSI (years) *M*=4.8(7.7) *Outcome data only reported for TBI group.	-Quality of life: Quality of Life After Brain Injury scale -Emotional and behavioural regulation: Neuro-QOL -Cognitive concerns: TBI-QOL -Positive affect and well-being: TBI-QOL	controlling for age, injury severity, gender, TSI, and number of classes taken. -Qualitative perceptions of improvements in resilience among individuals with TBI.
Dumont et al., 2004; Canada	Explored personal characteristics that contribute to resiliency in the context of improved social participation in adults with TBI.	Cross-sectional design. All participants had ongoing sequelae of TBI and received associated rehabilitation services for a period of 2-weeks to 14-months. Participants completed questionnaires and engaged in a 1:1 interview. Interview responses were analysed qualitatively.	Adults (*N*=53) with TBI (mild *n*=10, moderate *n*=18, severe *n*=24) Age *M*=37.0(8.7); 70% male; TSI (months) *M*=47(20.4)	-Resilience: Self-efficacy Scale; PER Test; semi-structured interview with open-ended questions -Social participation: LIFE-H	-Qualitatively measured personal characteristics that were found to best explain social participation were dynamism, perceived self-efficacy, and will. -The authors conclude that dynamism, perceived self-efficacy, and will constitute resiliency factors that could improve social participation in adults with TBI.
Elliott et al., 2017; USA	Examined the degree to which resilience personality characteristics are associated with symptoms of PTSD, symptoms of depression, and quality of life among Iraq/Afghanistan Veterans.	Longitudinal design. Participants recruited via mailings and advertisements to Veterans enrolled in a Veterans health care system. Participants participated in diagnostic interviews and completed self-report questionnaires upon enrollment into the study. Follow-up assessments were completed at 4- and 8-	Iraq/Afghanistan war Veterans (*N*=127) divided into two groups: 1. History of TBI during deployment (*n*=57; based on retrospective screening assessment using the BTBIS) 2. No history of TBI during deployment (*n*=70) Participants were also grouped based on personality prototypes using the MPQ: 1. Resilient (*n*=51) 2. Overcontrolled (*n*=27) 3. Undercontrolled (*n*=49)	-Resilience: CD-RISC -Personality: MPQ -Sleep quality: PSIQ -Health behaviours: HPLP -Distress tolerance: DT -Psychological inflexibility: AAQ-II -Coping: Brief COPE -Social Support: Deployment Risk and Resilience Inventory Postdeployment Social Support scale -PTSD symptoms: PCL-M -Depressive symptoms: BDI-II -Quality of life: VR-12; QLS	-Participants in the "Resilient" group had fewer sleep problems, reported more resilience and less psychological inflexibility, more health promotive behaviours, higher emotional distress tolerance, fewer PTSD and depressive symptoms over an 8-month period, and higher quality of life. These associations were independent of TBI status.

		months post-enrollment via mail.	Age *M*=37.64(10.54); 84% male		
Graham et al., 2013; USA	Evaluated the influence of serotonin transporter genotypes (5-HTTLPR) on the relationship between resilience and perceived limitations for community participation among Veterans with and without mild TBI.	Cross-sectional design. Veterans from Operation Enduring Freedom, Operation Iraqi Freedom, and/or Operation New Dawn who were enrolled in a larger parent study between 2010 and 2012 completed measures and genetic testing.	Veterans (*N*=67) divided into the following groups: 1. History of mild TBI (*n*=41; age *M*=31.8(7.6); 95% male) 2. No history of TBI (*n*=26; age *M*=33.2(9.1); 62% male)	-Resilience: CD-RISC -Function in community: CRIS -PTSD: PCL-C -TBI: Clinical Injury Questionnaire -Depressive symptoms: CES-D -PCS: NSI	-A history of TBI and being a 5-HTTLPR "long" carrier were both associated with lower resilience, with a combined additive effect.
Hanks et al., 2016; USA[2]	Examined the relative roles of demographic and theoretically resilience-related constructs (i.e., coping, social support, positive affectivity) on resilience among individuals with TBI.	Cross-sectional design. Participants who were 6-months to 5.5-years post-injury were recruited from a rehabilitation hospital TBI research registry. Participants completed measures in-person.	Adults (*N*=67) with complicated mild to severe TBI Median GCS=7 Age *M*=38.8(13.2); 85% male	-Resilience: CD-RISC -Cognition: WTAR; Trail Making Test B -Theoretically resilience-related variables: PANAS; CISS; SPS	-Resilience was not significantly directly associated with demographic characteristics, injury characteristics, premorbid intelligence, or cognitive flexibility. -Significant independent predictors of resilience included problem-solving coping style, perceived social support, trait positive and negative affectivity (overall, not individually), and social diversion. -Authors conclude that results provide support for good construct validity of the CD-RISC.
Kreutzer et al., 2016; USA	Examined resilience and its effect on psychosocial outcomes 3-months following moderate-to-severe TBI.	Cross-sectional design. Participants were recruited from an existing research database of individuals who were hospitalized and received inpatient rehabilitation due to a TBI. Study was a subset of a larger cohort parent study. Demographic information was	Adults (*N*=160) with moderate-to-severe TBI. GCS *M*=9.2(4.9) Age *M*=41.8(18.5); 76% male	-Resilience: CD-RISC -General functioning: DRS -Psychosocial outcomes: PART-O; SWLS; TBI-QOL; productivity at the time of injury categorized into two levels: productive (i.e., student, homemaker, employed) and non-productive (i.e., retired, unemployed, volunteer); pre-injury substance abuse	-CD-RISC scores were significantly lower than the general population. -Lower scores on the CD-RISC were significantly associated with less education, pre-injury substance abuse, and greater concurrent anxiety.

		collected during inpatient rehabilitation stay. Measures administered at approximately 3-months post-injury via telephone, in-person, or mail.			
Kreutzer et al., 2018; USA	Examined the efficacy of a structured, curriculum-based intervention (The Resilience and Adjustment Intervention) following TBI.	Two-arm, parallel, randomized controlled trial. Participants were referred by rehabilitation providers and randomized to either the treatment or waitlist group. Baseline data from both groups were collected prior to the initial intervention. The intervention consisted of 7 individual therapy sessions completed over a 5-week period. Post-treatment data were collected from both groups at the end of the 5-week treatment period. The waitlist group was provided the opportunity to complete the treatment thereafter. 3-month follow-up data were collected from the treatment group 10-14 weeks following the final session.	Adults (*N*=148) with a history of TBI. 1. Treatment group: *n* =75 2. Waitlist control group: *n*=73. Overall sample (no group differences in demographic or injury characteristics): Median age=42; 50% male 36% moderate-to-severe TBI, 59% mild TBI, 6% severity unknown Median TSI=1.6 years (range=3 months to 33 years)	-Resilience: CD-RISC -Additional outcome measures: MPAI-4l; 13-item stress test; BSI-18	-Improvements in all measures were observed between baseline and post-treatment, as well as baseline and 3-month follow-up for the treatment group, whereas measures for the waitlist control group remained relatively unchanged. -The treatment group demonstrated a significantly higher increase in resilience compared to the waitlist control group, and this increase was greater than the a-priori specified clinically significant change.
Laird et al., 2019; USA	Examined the degree to which social support, resilience, injury severity, and mTBI predicted affective balance (AB) among	Prospective longitudinal design. Participants with physical injury completed questionnaires prior to discharge from a trauma centre.	Adults (*N*=488) with physical injury (*n*=131 with mTBI) Age *M*=44.41(16.92), range=18-92 years; 36% female	-Resilience: CD-RISC -Social support: SPS -Injury severity: ISS -AB: Veterans RAND 12-Item Health Survey (Mental Health scale)	-Participants in the mTBI group reported lower resilience at initial assessment. -Resilience was positively associated with employment status.

	individuals with a history of physical injury (OI or mTBI).	Questionnaires were subsequently administered at 3-, 6-, and 12-month post-discharge follow-ups.			-Improvements in resilience predicted improvements in affective balance over time.
Laliberté Durish, Yeates, & Brooks, 2019; Canada	Examined anxiety and depressive symptoms as mediators of the relationship between resilience and PCS.	Cross-sectional design. Participants underwent a neuropsychological assessment at a hospital clinic due to poor recovery from a concussion. All measures included in the study were administered as part of the original neuropsychological assessment. All participants sustained concussions at least 1-month prior to assessment.	Adolescents (*N*=93) ages 13-18 years with a history of concussion. Age *M*=15.2(1.2); 56% female; TSI (days) *M*=178.8(106.1), range=42-473	-Resilience: CD-RISC -Anxiety/depressive symptoms: BASC-2 -PCS: PCSI	-Greater resilience significantly predicted greater self-reported (but not parent-reported) PCS, over and above the effects of age and sex. This relationship was no longer significant when anxiety or depressive symptoms were entered into the model. -Greater resilience significantly predicted fewer self- and parent-reported anxiety and depressive symptoms. -Self-reported anxiety symptoms significantly mediated the relationship between resilience and self-reported PCS. -Self- and parent-reported depressive symptoms significantly mediated the relationship between resilience and self-reported PCS. -Parent-reported depressive symptoms significantly mediated the relationship between resilience and parent-reported PCS. -Authors conclude that low psychological resilience is associated with greater anxiety and depressive symptoms, which, in turn, predict a combination of physical, cognitive, and fatigue-related PCS.
Laliberté Durish, Yeates, & Brooks, 2018a; Canada	Examined the role of resilience as a predictor of persistent PCS in children with a history of a single concussion, multiple concussions, or OI.	Cross-sectional design. Participants recruited from existing research databases derived from patients originally presenting to an emergency department	Children (*N*=75), ages 8-18 years, with a history of a single concussion (*n*=24), multiple concussions (*n*=24; range=2 to 8 previous concussions, *M*=3.04(1.62)), or OI (*n*=26)	-Resilience: CD-RISC -PCS: PCSI	-Greater resilience was a significant unique predictor of fewer child-reported (but not parent-reported) PCS. -No groupXresilience moderation effects were significant. -Greater resilience was a significant predictor of fewer child- and parent-

		and outpatient clinics with concussion or OI. All participants sustained injuries at least 6 months prior to enrollment.	Age *M*=14.2(2.88); 52% female; TSI (months) *M*=32.94(19.59), range=6.51-130.66		reported emotional PCS, as well as fewer child-reported fatigue PCS, even after accounting for group effects.
Laliberté Durish, Yeates, & Brooks, 2018b; Canada	Examined the construct validity of the CD-RISC in a pediatric concussion and OI sample.	Cross-sectional design. Participants recruited from existing research databases derived from patients originally presenting to an emergency department and outpatient clinics with concussion or OI. All participants sustained injuries at least 6-months prior to enrollment.	Children (*N*=75), ages 8-18 years with a history of 1 or more prior concussions (*n*=49) or OI (*n*=26) Age *M*=14.2(2.88); 52% female; TSI (months) *M*=32.94(19.59), range=6.51 to 130.66	-Resilience: CD-RISC (10- and 25-item measures) -Convergent validity measures: CAPS; SDQ; BASC-2; PedsQL -Divergent validity measure: CNS Vital Signs Reaction Time	-25-item CD-RISC: Among children with concussion, greater resilience was associated with fewer self-reported general behavioural problems, lower levels of self-reported depressive symptoms, and better self-reported quality of life. In the overall sample, greater resilience was unexpectedly related to poorer scores on the CNS Vital Signs Reaction Time, though this relationship was not observed when the groups were analysed separately. -10-item CD-RISC: Among children with concussion, in addition to the correlations listed for the 25-item (although, correlations were significantly larger with the 10-item), greater resilience was also associated with fewer parent-reported general behaviour problems, lower self-reported anxiety, and better parent-reported quality of life. 10-item CD-RISC was not correlated with CNS Vital Signs Reaction Time. -Concussion and OI groups did not differ in their correlations among the CD-RISC and convergent/divergent validity measures. -Authors conclude that results provide support for construct validity of the CD-RISC when used in a pediatric concussion/OI population, with greater support for the construct validity of the 10-item CD-RISC.

Losoi et al., 2015a; Finland	Examined the role of resilience as a predictor of recovery from fatigue following mild TBI.	Prospective, longitudinal design. Subset of a larger parent study. Participants recruited from an emergency department (ED) due to sustainment of either a mild TBI or OI. Participants participated in a clinical assessment and MRI on the day of their presentation to the ED. Participants completed self-report questionnaires at 1- and 6-months post-injury via the internet. Depressive symptoms were evaluated during a neuropsychology follow-up at 1-month post-injury.	Adults (*N*=101) with mild TBI (*n*=67; age *M*=37(12); 63% male) and OI (*n*=34; age *M*=39.1(12.8); 56% male).	-Resilience: RS -Fatigue: BNI-FS. -Injury severity: INS -Insomnia: ISI -Pain: RNBI -Depressive symptoms: BDI-II	-Mild TBI and OI groups did not significantly differ on pain, depressive symptoms, or resilience. -Resilience and fatigue were significantly negatively correlated at 1- and 6-months post-injury in the mild TBI group. -Resilience was a significant predictor of change in fatigue (i.e., recovery from fatigue) from 1- to 6-months post-injury in the mild TBI group, even after accounting for other variables thought to be associated with fatigue (i.e., depression, sleep disorders, pain).
Losoi et al., 2015b; Finland	Examined resilience as measured by the Resilience Scale (RS) in mild TBI, as well as the association between resilience and outcome following mild TBI.	Prospective, longitudinal design. Participants recruited from the emergency department (ED) following sustainment of a mild TBI or OI. Participants underwent a clinical interview upon presentation to the ED/enrollment in the study. Participants completed self-report questionnaires via internet at 1-, 6-, and 12-months post-injury, and depressive symptoms were evaluated at a neuropsychological	Adults (*N*=113) with mild TBI (*n*=74; age *M*=37(11.8); 61% male) and OI (*n*=39, age *M*=39.7(12.1); 49% male)	-Resilience: RS -PCS: RPCSQ -Fatigue: BNI-FS -Insomnia: ISI -Pain: RNBI -PTSD: PCL-C -Depressive Symptoms: BDI-II -Quality of life: QOLIBRI	-No statistically significant difference in resilience among the mild TBI and OI groups at any time points. -Resilience was relatively stable from 1- to 6- and 12-months in both groups. -In the mild TBI group, greater resilience was associated with less fatigue, less traumatic stress, and better quality of life at 1-month post-injury; less fatigue, less depression, and better quality of life at 6-months post-injury; fewer PCS, less fatigue, less insomnia, less traumatic stress, and better quality of life at 12-months post-injury. -Resilience measured at 1-month was not associated with return to work. -Internal consistency reliability of the RS was high for both groups.

		follow-up assessment at 1- and 6-months post-injury.			
Losoi et al., 2016; Finland	Characterized recovery from mild TBI in a sample of previously healthy adults.	Prospective longitudinal design. Participants were recruited upon presentation to the emergency department (ED) following sustainment of a mild TBI or OI. Participants underwent a clinical interview upon presentation to the ED/enrollment in the study. Participants completed self-report questionnaires via internet at 1-, 6-, and 12-months post-injury. Neuropsychological functioning and depressive symptoms were evaluated at 1-month (both groups) and 6-month (mild TBI group only) follow-ups.	Adults (*N*=114) with mild TBI (*n*=74; age *M*=37(11.8); 39% female) and OI (*n*=40, age *M*=40.1(12.2), 50% female)	-Resilience: RS -Disability: GOS-E -PCS: RPCSQ -Fatigue: BNI-FS -Insomnia: ISI -Pain: RNBI -PTSD: PCL-C -Depressive Symptoms: BDI-II -Quality of life: QOLIBRI -Neuropsychological functioning: RAVLT; Stroop Test; Trail Making Test; Verbal Fluency; FTT; WAIS-III Information, Digit Span, Digit-Symbol Coding, Symbol Search	-Participants who endorsed mild postconcussive syndrome at 12 months were more likely to report significantly greater symptoms of fatigue, insomnia, and traumatic stress, lower resilience, lower quality of life, and poorer life satisfaction than those who did not meet criteria for mild postconcussive syndrome. -For the participants with mild TBI that met criteria for mild postconcussive syndrome at 12-months post-injury, 37.5% also met criteria for low resilience at 1-month post-injury.
Lukow et al., 2015; USA	Investigated the role of resilience in a post-acute TBI sample, as well as the relationship between resilience and psychological health.	Cross-sectional design. Participants were self-referred or referred by a professional to participate in a larger parent study designed to promote resilience after brain injury. Participants completed measures utilised in the current study at baseline upon enrollment into the parent study.	Adults (*N*=96) with mild to severe TBI. Age *M*=40.5(12.95); 45% male; 72% hospitalized for TBI with an average length of stay of 19.1(20.45) days. TSI (years) *M*=2.1(2.08), range=3 months to 9 years; GCS (data available for only 64% of participants) *M*=10.9(5.0)	-Resilience: CD-RISC -Adaptability functioning: MPAI-4 -Psychological distress: BSI-18	-Greater resilience was significantly associated with fewer difficulties with adaptability and psychological distress. After controlling for each of the constructs within both scales, however, only the adjustment score (on the MPAI-4) and the depression score (on the BSI-18) were significantly correlated with resilience. -Significant differences in resilience scores were present among individuals who met criteria for psychological distress on the BSI-18, and those who

					did not (i.e., lower resilience was related to higher rates of psychological distress caseness). -No significant differences were present with regards to the relationship between resilience and gender, injury severity, or TSI.
Marwitz et al., 2018; USA	Examined (1) the trajectory of resilience during the first year following moderate-to-severe TBI, (2) factors associated with resilience at 3-, 6-, and 12-months post-injury, and (3) changing relationships between resilience and demographic/injury characteristics over time.	Prospective longitudinal design. Participants were recruited from an existing research database of individuals who were hospitalized and received inpatient rehabilitation due to a TBI. Demographic information was collected during inpatient rehabilitation stay. Follow-up measures administered at approximately 3-, 6-, and 12-months post-injury via telephone, in-person, or mail.	Adults (*N*=192) with moderate-to-severe TBI. Age *M*=42.5(18.8); 76% male; GCS median = 8	-Resilience: CD-RISC -Disability: DRS -Social engagement: PART-O -Life satisfaction: SWLS -Quality of life/anxiety and depressive symptoms: TBI-Quality of Life Anxiety and Depression Scales derived from the Patient-Reported Outcomes Measurement Information System and the Quality of Life in Neurological Disorders measurement systems -Productivity at the time of injury categorized into two levels: productive (i.e., student, homemaker, employed) and non-productive (i.e., retired, unemployed, volunteer) -Pre-injury substance abuse	-Resilience scores remained relatively stable across time. However, when race, education, preinjury substance abuse, anxiety, life satisfaction, and disability level were accounted for, resilience declined during the first year (change minimal and not thought to be of clinical significance). -Participants who were white, married, and were labelled as "productive" preinjury had higher resilience scores than their counterparts. -Participants with less than a high school education tended to have the lowest levels of resilience. -Lower levels of anxiety, depression, and disability, and higher life satisfaction and social engagement were associated with greater resilience at each time point. The relationship between resilience and each of these factors did not change over time (with exception to anxiety, wherein there was a moderating effect of time). -No significant relationship between resilience and sex or age.
McCauley et al., 2013; USA	Examined the role of pre-injury resilience and mood status in the prediction of anxiety and PCS severity following sustainment of a mild TBI.	Prospective longitudinal design. Participants were recruited from Level-I trauma centres following sustainment of a mild TBI or OI. Participants were administered a baseline assessment <24	Adults (*N*=75) with mild TBI (*n*=46; age *M*=30.6(9.6), 6:23 female:male ratio; GCS *M*=14.91(0.28)) or OI (*n*=29, age *M*=26.7(7.5), 11:35 female:male ratio)	-Resilience: CD-RISC -Depressive symptoms: CES-C -Acute Stress: ASDS -PTSD symptoms: PCL-C -PCS: RPCSQ	-Groups did not differ on pre-injury resilience. -Pre-injury proxies of depressive symptoms and resilience were significantly negatively correlated (i.e., higher resilience = fewer depressive symptoms).

		hours post-injury, including acquisition of a proxy of preinjury mood and resilience. In-person follow-up assessments were conducted at 1-week and 1-month post-injury.			-Higher preinjury resilience was significantly associated with lower PCS severity and acute stress at 1-week post-injury. -Higher preinjury resilience was associated with higher anxiety and PCS severity at 1-month post-injury.
Merritt, Lange, & French, 2015; USA	Examined the relationship between resilience and PCS/PTSD symptom reporting following mild TBI in military service members.	Cross-sectional design. Subset of a larger parent study wherein participants were recruited prospectively after being screened positive for TBI by a medical staff within the first few days of arrival to a military medical centre. Participants completed questionnaires as part of the larger parent study.	US military service members (*N*=142) who sustained an uncomplicated mild TBI as a result of a combat or non-combat related incident. Age *M*=27.6(7.9); 89% male TSI (months) *M*=1.9(2.8)	-Resilience: RSES (three theoretically defined resilience groups were created based on participants' mean item score: moderate resilience, high resilience, very high resilience) -PCS: NSI (responses also used to determine if participants met DSM-IV-TR criteria for postconcussional disorder -PTSD symptoms: PCL-C	-Greater resilience was significantly associated with fewer overall PCS as well as fewer cognitive and affective PCS (no relationship between resilience and somatic/sensory PCS). -Greater resilience significantly associated with fewer PTSD symptoms. -The moderate resilience group reported a significantly greater number of affective PCS compared to the high and very high resilience groups, as well as a greater number of cognitive PCS compared to the very high resilience group. -The moderate resilience group reported a significantly greater number of PTSD symptoms compared to the very high resilience group. -Lower resilience significantly predicted the presence of postconcussional disorder and PTSD.
Oldenburg et al., 2018; Sweden	Investigated aspects of "emotional reserve", psychological variables, and psychiatric vulnerability, and their association with PCS 1-year following mild TBI.	Prospective longitudinal design. Subset of a larger parent study. Self-reported PCS ratings were collected 1-day post-injury, a psychiatric assessment was conducted 7-days post-injury, and follow-up self-report measures	Adults (*N*=94) with mild TBI who reported 3 or more PCS and 3 or more disabilities at 1-year post-injury (i.e., PCS group; *n*=11; age *M*=41.9(13.2); 27% male) or fewer than 3 PCS/disabilities at 1-year post-injury (i.e., recovered group; *n*=83; age *M*=36.7(15.2); 65% male	-Resilience: SOC -Psychological and environmental stressors: Severity of Psychosocial Stressors Scale -PCS: RPCSQ -Disability: RHFUQ -Anxiety and depressive symptoms: HADS -Stress reactions: IES-R	-The PCS group reported significantly lower resilience compared to the recovered group, with a significant independent contribution of the SOC manageability scale (i.e., control over one's life, sense of mastery).

		were completed via mail-out 1-year post-injury.		-Preinjury behaviour and personality: SSP -Alcohol use: AUDIT	
Poritz et al., 2020; USA	Evaluated the responsiveness of the TBI-QOL as a predictor of productivity among adults with TBI.	Prospective longitudinal design. Subset of a larger parent study. Participants were recruited from rehabilitation hospitals and completed self-report measures of productivity and quality of life. Measures were repeated at a 6-month follow-up.	Adults (*N*=201) with a history of mild, moderate, or severe TBI were divided into 3 groups based on change in productivity over 6 months: Increased productivity (*n*=72), Decreased productivity (*n*=71), No change in productivity (*n*=58) Overall Sample: Age *M*=37.5(13.4), range=18-64 years; 27% female; TSI (years) *M*=5.1(6.4), TSI range=0.05-40.44 years	Resilience: TBI-QOL Productivity: PART-O	-The increased productivity group reported clinically meaningful improvements in resilience compared to the decreased productivity or no change in productivity groups.
Rapport, Wong, & Hanks, 2019; USA	Examined resilience as a predictor of functional and subjective well-being outcomes following TBI, independent of the effects of affectivity.	Cross-sectional design. Participants were consecutively recruited from a hospital and completed measures at a single time point.	Adults (*N*=67) with complicated mild to severe TBI Age *M*=38.8(13.2); 15% female; Median GCS=7	-Resilience: CD-RISC -Estimated premorbid IQ: WTAR -Affectivity: PANAS -Objective well-being: MCIRS; DRS -Subjective well-being: SF-12 Healthy Survey; SWLS; CIM	-Resilience was associated with better objective and subjective well-being outcomes, even after accounting for positive affectivity. -Significant relationship among resilience and physical health-related objective well-being, even after controlling for negative affectivity. -Stronger relationship observed among those with low resilience, as compared to those with average or high resilience. -Relationships among resilience and subjective mental health, satisfaction with life, and community integration remained significant after controlling for negative affectivity. -Estimated premorbid IQ was not correlated with resilience. -Authors conclude that the relationship of resilience to objective functional disability, but not general physical health

					or aspects of subjective well-being, may be partially accounted for by negative affectivity.
Reid et al., 2018; USA	Examined (1) the impact of adversity and resilience on PCS and post-traumatic stress reporting among active duty military service members who sustained a mild TBI, (2) whether specific adverse events are associated with more or less symptom endorsement, (3), whether the age at which adverse events are first experienced impacts symptom reporting, and (4) whether an interaction effect on symptom reporting exists between resilience and adversity.	Cross-sectional design. Service members who screened positive for a brain injury during a primary care visit were recruited into the larger parent study. Participants engaged in clinical interviews and completed self-report measures.	Active duty military service members (*N*=165) with mild TBI. Age *M*=31.4(6.4); 90% male TSI (months) *M*=54.7(43.8) months.	-Resilience: CD-RISC -Adversity: Trauma History Screen (summed total of positively endorsed traumatic experiences) -PCS: NSI -PTSD symptoms: PCL-C	-Greater resilience was significantly associated with fewer PCS and symptoms of post-traumatic stress. -Resilience and adversity were not significantly correlated.
Sela-Kaufman et al., 2013; Israel	Examined (1) whether premorbid personality factors ("Big 5" personality traits, attachment style, temperament; all treated as proxies of reserve/resilience) predicted social, occupational, and psychological functioning, and (2) whether the factors moderate the influence	Cross-sectional design. Participants were recruited through a day-treatment brain injury rehabilitation unit at a medical centre and through a Veterans TBI rehabilitation centre. All participants were involved in physical rehabilitation, as well as social, emotional, and occupational therapy programs for an average	Adults (*N*=61) with moderate-to-severe TBI, Age at assessment *M*=37.9(12.2), range=21-63 years; age at injury *M*=26.1(7.73), range=19-58 years; 93% male GCS *M*=6.24(3.21)	-Premorbid personality (i.e., resilience/reserve proxy): Personality traits (NEO-EFI); Attachment Style (Attachment Style questionnaire); Temperament (Emotional-Activity-Sociability-Shyness questionnaire) -Social functioning: Social Activity Questionnaire -Occupational functioning: Occupation Level Index -Psychological symptoms: BSI	-Personality traits significantly predicted social and occupational functioning. -Attachment style significantly predicted occupational and psychological functioning. -Temperament did not predict any of the outcome measures. -Only the personality traits of neuroticism, extraversion, and conscientiousness significantly moderated the influence of injury severity on only occupational functioning (occupational dysfunction resulted for all individuals with

	of TBI severity on outcomes.	of 11.82 years (*SD*=12.86). Participants were assessed at least 1-year post-injury. Upon enrollment, participants completed questionnaires assessing psychological and adaptive functioning. Retrospective premorbid personality factors were obtained via questionnaires completed by participants' family members.			prolonged LOC, however, individuals low on neuroticism adapted much better than individuals high on neuroticism as the duration of LOC became briefer; for individuals high on extraversion, prolonged duration of LOC adversely affected occupational functioning whereas lower LOC durations were associated with more favourable outcomes for high extraverts; for individuals high on conscientiousness, reduced duration of LOC was associated with better occupational functioning). -Avoidant attachment style significantly moderated the influence of injury on occupational functioning (for individuals low on avoidant attachment, reduced LOC was associated with better occupational functioning. -Authors conclude that among the three potential personality constructs hypothesized to reflect reserve, premorbid "Big 5" personality traits are most relevant in moderating the impact of injury severity on outcome. Thus, adaptive personality features may contribute to resilience against negative effects of TBI, whereas maladaptive traits may lead to reduced adaptive functioning.
Sherer et al., 2015; USA	Examined (1) dimensions of cognitive impairment, self-reported symptoms/strengths, and environmental facilitators used to characterize recovery from TBI in the post-acute period, and (2)	Cross-sectional design. Participants recruited from a database of individuals who had previously participated in research at various clinics and rehabilitation sites. All participants were living in the community. Data were	Adults (*N*=504) with a history of TBI (33% severe, 10% moderate, 26% mild). Age *M*=38.2(13); 75% male; TSI (years) *M*=6.3(6.8)	-Resilience: TBI-QOL Emotional Health domain (Resilience sub-domain) -Cognitive functioning: RAVLT; Trail Making Test; WMT; Verbal Fluency Test; WAIS-IV Symbol Search, Coding, Letter-Number Sequencing	-Higher levels of resilience were associated with more favourable levels of community participation following TBI.

	evaluated their roles as predictors of social/community participation outcome following TBI.	collected via medical record review, interview, and administration of questionnaires and cognitive tests.		-Psychological functioning: PROMIS Emotional Support Scale; Economic Quality of Life Scale; PHQ-9; GAD-7; FAD -PCS: RPCSQ; NSI -Social/community participation: PART-O.	
Sigurdardottir et al., 2014; Norway	(1) Examined the longitudinal trajectories of emotional distress 3-months, 1-year, and 5-years following TBI, and (2) compared emotional distress trajectory membership with demographic, injury, and self-reported variables.	Prospective longitudinal design. Participants were recruited upon hospital admission following sustainment of a TBI and completed follow-up assessments (questionnaires) at 3-months, 1-year, and 5-years post-injury. Data were analyzed using growth mixture modelling to identify homogeneous groups that shared similar emotional distress symptom profiles over time.	Adults (*N*=117) with TBI. Four emotional distress trajectories were identified: -Chronic (*n*=6): High emotional distress symptoms at all time points; age at injury *M*=36.7(12.5); 17% female; GCS *M*=13.7(1.5) -Delayed (*n*=8): Low emotional distress symptoms at 3-months and 1-year, high emotional distress symptoms at 5-years; age at injury *M*=31.3(13.3); 47% female; GCS *M*=9.8(3.8) -Recovery (*n*=17): High emotional distress symptoms at 3-months and 1-year, low emotional distress symptoms at 5-years; age at injury *M*=34.9(12); 47% female; GCS *M*=10.9(4.5) Resilience (*n*=86): Low emotional distress symptoms at all time points; age at injury *M*=31.7(10.07); 27% female; GCS *M*=9.7(4.2)	-Emotional distress/PTSD: IES-R (resilience defined as absence of emotional distress/PTSD symptoms) -Stressors: Event-Related Stressors Index -Coping style: Coping Style Questionnaire -Anxiety/depressive symptoms: HADS -Drug/alcohol dependency: Cut down, Annoyed, Guilty, Eye-opener questionnaire -Injury severity: Abbreviated Injury Scale; Injury Severity Score	-The majority of participants (73.5%) displayed a resilience trajectory. -The chronic group demonstrated poorer outcomes on scales measuring emotional distress, anxiety/depressive symptoms, event-related stressors, and coping styles. -The recovery group demonstrated greater anxiety/depressive symptoms at 3-months and 1-year compared to the resilience group. -Recovery and chronic groups endorsed more avoidant-focused coping than the resilience group. -The chronic group endorsed significantly greater substance abuse pre-injury and at 1-year compared to the other groups. -Employment rates were highest in the resilience group pre-injury and at 1-year. -Psychiatric problems were endorsed more in the recovery and chronic groups pre-injury and at 1-year compared to the resilience and delayed groups. -Groups did not differ on other demographic or injury variables.
Sima et al., 2019; USA	Examined the role of resilience, measured soon after injury, as a predictor of outcome at	Prospective longitudinal design. Study utilized data from a research database. Participants	Adults (*N*=158) with TBI. Age at injury *M*=42.4(18.3); 76% male	-Resilience: CD-RISC -Life satisfaction: SWLS -Social relations: PART-O -Quality of Life: TBI-QOL	-Greater resilience (measured shortly after injury) significantly predicted better life satisfaction, less anxiety, less depression, successful return to work,

	1- and 2- years following TBI.	were originally recruited from trauma centres within 72 hours of injury. All participants underwent inpatient rehabilitation. Demographic and lifestyle characteristics were collected from participants and/or family members during inpatient rehabilitation. Post-injury characteristics of resilience, depression, anxiety, satisfaction with life, employment, substance abuse, and social relations were collected at 3- or 6-months post-injury. Follow-up outcome measures (life satisfaction, social relations, quality of life) were completed at 1- and 2-years post-injury.	GCS *M*=9(4.8)	-Other variables of interest: return to work, substance abuse	and less substance misuse at 1- and 2-years post-injury. Resilience did not predict social relations. -Resilience achieved better predictions for 1-year outcomes than 2-year outcomes.
Sullivan et al., 2015; Australia	Examined whether perceived psychological resilience is a significant contributor of PCS reports in mild TBI.	Cross-sectional design. Participants were recruited via advertisements. Enrollment criteria were self-reported sustainment of a mild TBI between 1- and 6- months prior to recruitment or no history of mild TBI. Participants completed measures online.	Adults (*N*=233) with mild TBI (*n*=35; age *M*=22.32(5.94); 43% male) and healthy controls (*n*=198; age *M*=22.84(7.63); 18% male)	-Resilience: BRS -PCS: NSI	-Greater resilience was significantly associated with higher education levels and gender (males more likely to report lower resilience than females). -Greater PCS was associated with a positive mild TBI history and lower resilience. -Resilience accounted for the most variance in PCS.

Vos et al., 2019; USA	Evaluated the impact of resilience on social participation outcomes in the context of emotional distress in individuals with a history of TBI.	Prospective longitudinal design. Participants were recruited from inpatient rehabilitation facilities and completed cognitive and self-report measures at two time points, 6 months apart.	Adults (*N*=201) with a history of TBI (30% mild) Age *M*=37.5(13.4), range=18-64 years; 27% female; TSI (years) *M*=5.1(6.4), TSI range=0.05-40.44 years	-Resilience: TBI-QOL -Social participation: PART-O	-Greater resilience was associated with a higher ability to participate at baseline. -Greater resilience was associated with greater satisfaction and social participation, over and above emotional distress. These effects were greatest among those with low to moderate levels of distress (negligible effects among those with high distress). -Resilience was not significantly associated with participation outcomes at 6-months. -Resilience with moderately, indirectly associated with emotional distress.

AAQ-II = The Acceptance and Action Questionnaire-II; ASDS = Acute Stress Disorder Scale; AUDIT = Alcohol Use Disorders Identification Test; AVLT = Auditory Verbal Learning Test; BCT = Booklet Category Test; BDI-II = Beck Depression Inventory-II; BI = Barthel Index; BNI-FS = Barrow Neurological Institute Fatigue Scale; BRS = Brief Resilience Scale; BSI-18 = Brief Symptom Inventory-18; BTBIS = The Brief Traumatic Brain Injury Screen; CANTAB = Cambridge Neuropsychological Testing Automated Battery; CCT = Children's Category Test; CD-RISC = Connor-Davidson Resilience Scale; CES-D = Centre for Epidemiologic Studies Depression Scale; CIM = Community Integration Measure; CISS = Coping Inventory for Stressful Situations; CRIq = Cognitive Reserve Index questionnaire; CRIS = Community Reintegration of Service Members Instrument; CVLT = California Verbal Learning Test; CVLT-C = California Verbal Learning Test-Children's Version; DIS-III-A = Diagnostic Interview Schedule, Version III-A; DRRI = Deployment Risk and Resilience Inventory; DRS = Disability Rating Scale; DT = The Distress Tolerance Inventory; FIM = Functional Independence Measure; FTT = Finger Tapping Test; GOS-E = The Extended Glasgow Outcome Scale; HBI = Health and Behaviour Inventory; HPLP = Health-Promoting Lifestyle Profile II; IES-R = Impact of Event Scale; ISI = Insomnia Severity Index; ISS = Injury Severity Score; LCF = Rancho Los Amigos Levels of Cognitive Functioning scale; LIFE-H = Assessment of Life Habits; MCIRS = Modified Cumulative Illness Rating Scale; MPAI-4 = Mayo Portland Adaptability Inventory; MPQ = Multidimensional Personality Questionnaire Brief Form; NEO-EFI = Neuroticism-Extraversion-Openness Five Factor Inventory; Neuro-QOL = Neurology Quality-of-Life; NSI = Neurobehavioural Symptom Inventory; PANAS = Positive and Negative Affect Schedule; PCL-C = PTSD-Checklist-Civilian Version; PCL-M = PTSD Checklist-Military Version; PCS-I = Postconcussive Symptom Interview; PER Test = Test de personnalité; PSIQ = Pittsburgh Sleep Quality Index; QLS = The Quality of Life Scale; QOLIBRI = Quality of Life after Brain Injury; RAVLT = Rey Aditory Verbal Learning Test; RCFT = Rey Complex Figure Test; RHFUQ = Rivermead Head Injury Follow-up Questionnaire; RNBI = Ruff Neurobehavioural Inventory; RPCSQ – Rivermead Post-Concussion Symptom Questionnaire; RS = The Resilience Scale; RSES = Response to Stressful Experiences Scale; SOC = Sense of Coherence Scale; SPS = Social Provision Scale; SSP = Swedish Universities Scales of Personality; SWLS = Satisfaction with Life Scale; TBI-QOL = Traumatic Brain Injury-Quality of Life; TEA-Ch = Test of Everyday Attention for Children; ToPF = Wechsler Advanced Clinical Solutions Test of Premorbid Function; TMT = Trail Making Test; VMI = Developmental Test of Visual-Motor Integration; VR-12 = Veterans Rand 12-item; WAIS-III = Wechsler Adult Intelligence Scale – Third Edition; WAIS-IV = Wechsler Adult Intelligence Scale-Fourth Edition; WAIS-R = Wechsler Adult Intelligence Scale-Revised; WASI = Wechsler Abbreviated Scale of Intelligence; WCST = Wisconsin Card Sorting Test; WMS/WMS-R = Wechsler Memory Scale/Wechsler Memory Scale-Revised; WRAT-3 = Wide-Range Achievement Test-Third Edition; WTAR = Wechsler Test of Adult Reading

*$p < .05$ interpreted as significant
[1] Study examines both cognitive and brain reserve
[2] Study examines both resilience and cognitive reserve

Measurement of Reserve and Resilience

Cognitive Reserve

Measurement of cognitive reserve varied across studies. The majority of studies that examined the role of cognitive reserve measured estimated premorbid IQ (7 studies), years of education (1 study), or a combination of IQ, education, or occupational attainment as a proxy of cognitive reserve (7 studies). Estimated premorbid IQ was measured using the Test of Premorbid Functioning (2 studies), Wechsler Test of Adult Reading (2 studies), National Adult Reading Test (2 studies), Wechsler Individual Achievement Test – Second Edition (Word Reading subtest; 1 study), Wechsler Intelligence Scale for Children – Fourth Edition (Vocabulary subtest; 1 study), Wechsler Adult Intelligence Test – Third Edition (Information, Vocabulary, and Matrix Reasoning subtests; 2 studies), General Technical Test (1 study), and the Oklahoma Premorbid Intelligence Estimate (1 study). One study (Fay et al., 2010) calculated a composite score based on performance across a range of cognitive tests (i.e., WASI; WRAT-3; CVLT-C; VMI; CANTAB Pattern Recognition Memory, Stockings of Cambridge, Spatial Working Memory). This composite score of cognitive ability, which the authors justified as unaffected by mTBI and therefore reflective of premorbid functioning, was utilized as a proxy of cognitive reserve. Two studies (Donders & Kim, 2019; Mahdavi, Hasper, & Donders, 2019) examined parental education as a proxy of children's cognitive reserve. One study (Levi et al., 2013) included measures of premorbid SES and premorbid leisure activity (Lifetime of Experience Questionnaire), in addition to estimated premorbid IQ, in a composite proxy of cognitive reserve. One study (Luis, Vanderploeg, & Curtiss, 2003) included retrospective aptitude/achievement test scores as a proxy of cognitive reserve (one of American College Testing Program, Stanford Binet, Differential Aptitude Test, Stanford Achievement Test, General Aptitude Test Battery, or Armed Services Vocational Aptitude Battery). Lastly, one study (Menardi et al., 2020) included a self-report cognitive reserve questionnaire (Cognitive Reserve Index questionnaire) that captured education, working activity, and leisure activity.

Brain Reserve

The only study to examine the role of brain reserve relative to TBI utilized total intracranial volume as a proxy of brain reserve (Kesler et al., 2003).

Resilience

Methods for measuring resilience were less variable; all studies measured resilience via self-report questionnaires, with a focus on individual psychological qualities or characteristics. Among self-report measures used to measure resilience, 27 studies included resilience-specific measures: Connor-Davidson Resilience Scale (CD-RISC; 17 studies), TBI-Quality of Life (Resilience sub-domain; 4 studies), The Resilience Scale (3 studies), Self-Efficacy Scale (1 study), Response to Stressful Experiences Scale (1 study), Sense of Coherence Scale (1 study), or Brief Resilience Scale (1 study). One study (Arbour et al., 2017) measured resilience qualitatively through the use of a semi-structured interview, in combination with responses on the CD-RISC. Three studies included the use of self-report personality measures as proxies of resilience. One study (Elliott et al., 2017) grouped participants into a "resilient" group based on responses on the Multidimensional Personality Questionnaire, in addition to examining responses on the CD-RISC. Another study (Sela-Kaufman et al., 2013) examined responses on a combination of the Neuroticism-Extraversion-Openness Five Factor Inventory, Attachment Style Questionnaire, and the Emotional-Activity-Sociability-Shyness Questionnaire to examine the impact of "adaptive" personality styles as factors related to resilience. A third study (Dumont et al., 2004) examined personality characteristics endorsed on the Test de Personalité in relation to the construct of resilience. Lastly, one study (Sigurdardottir et al., 2014) defined resilience as low endorsement of symptoms of emotional distress on the Impact of Event Scale.

Construct Validity and Mechanisms of Reserve and Resilience in TBI

Cognitive Reserve

Eight studies commented on construct validity or factor structure of proxies of cognitive reserve, and/or mechanisms of cognitive reserve as a predictor of outcome in TBI (Krch et al., 2019; Mahdavi, Hasper, & Donders, 2019; Leary et al., 2018; Steward et al., 2018; Levi et al., 2013; Fuentes, McKay, & Hay, 2010; Schiebel et al., 2009; Ropacki & Elias, 2003). Two of those studies commented on the validity of proxies of cognitive reserve when applied in a TBI population. The study conducted by Fuentes, McKay, & Hall (2010) did not provide support for the use of traditional proxies of cognitive reserve (i.e., reading/vocabulary measures to capture premorbid cognitive functioning) in a pediatric TBI population. This study concluded that reading ability and vocabulary do not capture pre-injury functioning in children, and thus are not valid proxies of cognitive reserve in this population. Their conclusions were supported by null findings with respect to the relationship among reading ability and vocabulary to cognitive outcomes following TBI, and thus, an inability to replicate findings of such relationships documented in adult populations. Findings from the Leary and colleagues (2018) study indicated more support for the use of estimated premorbid IQ as a proxy of cognitive reserve (i.e., correlated with a greater number of neuropsychological outcomes) than occupational attainment.

One study, conducted by Levi et al. (2013), reported on the factor structure of cognitive reserve in a TBI population. Specifically, the authors conducted a factor analysis of several traditional proxies of cognitive reserve and reported a three-factor model of estimated premorbid IQ, socioeconomic status, and leisure activity to represent separate latent variables that underpin cognitive reserve in TBI. They concluded that cognitive reserve represents a multidimensional construct rather than a unitary one.

With regards to stability of cognitive reserve, Ropacki & Elias (2003) reported on the association of premorbid factors such as history of alcoholism, drug abuse, psychiatric problems, and previous neurological insult, with scores on proxies of cognitive reserve (i.e., estimated premorbid IQ, education, occupational attainment). Their findings supported the conclusion that life history factors associated with changes in neurological functioning are likely reflected within classic proxies of cognitive reserve, indicating that cognitive reserve may not be a stable factor. Furthermore, two studies, conducted by Steward and colleagues (2018) and Mahdavi, Hasper, & Donders (2019), reported that individuals with worse injury severity demonstrated lower estimated pre-morbid IQ and parental education levels, respectively, raising concerns about the validity of estimated premorbid IQ measures in terms of their robustness to the effects of more severe brain injury, as well as parent education as a proxy of a child's cognitive reserve. On the contrary, 3 studies indicated that traditional cognitive reserve proxies are robust to the influence of injury. Specifically, Krch et al. (2019) reported that estimated premorbid IQ was not correlated with neuropathology as measured by fractional anisotropy, indicating robustness of estimated premorbid IQ measures to the effects of injury. Further, Schiebel et al. (2009) reported that TBI and OI groups did not differ on estimated premorbid IQ or educational attainment, findings that were mirrored by Ropacki & Elias (2003) who found no TBI severity group differences on measures of estimated premorbid IQ.

Underlying mechanisms of cognitive reserve were explored in studies conducted by Schiebel et al. (2009) and Steward et al. (2018), though their findings were somewhat contradictory. Specifically, the Schiebel et al. (2009) study supported a compensatory model of reserve due to correlations among reserve factors and elevated brain activation during cognitive task engagement (i.e., higher education was found to be associated with greater activation of more neural networks in individuals with TBI, as compared to OI). However, the study conducted by Steward and colleagues (2018) supported a neural efficiency model of cognitive reserve rather than a compensatory model, given that cognitive reserve was not found to predict the rate of cognitive recovery, thereby leading the authors to conclude that alternate neural networks were not likely being recruited to compensate for the demand on recovering networks. Rather, the authors concluded that preservation of the relationship among intelligence and cognitive functioning post-injury represents the underlying mechanism of cognitive reserve in this population (i.e., cognitive reserve was described as high efficiency and capacity of existing neural networks in providing protection from disruption of functioning, rather than reorganization of networks to compensate for cognitive demands). A third study reported support for what the authors describe as an "active" model of reserve based on findings that individuals with greater cognitive reserve demonstrated greater cognitive recovery, even after accounting for initial performance (Fraser et al., 2019). However, the authors did not comment on whether these findings specifically provide support for efficiency versus compensatory mechanisms of cognitive reserve.

Brain Reserve

The Kelser et al. (2003) study that examined the role of brain reserve in the context of TBI suggested that TICV, measured as a proxy of brain reserve, is not impacted by injury severity. Furthermore, the impact of TICV as a protective factor against poor cognitive outcomes post-injury was apparent irrespective of injury severity. The authors concluded that their results provide support for a passive model of reserve.

Resilience

Six studies reported on the construct validity of resilience proxies (Oldenburg et al., 2018; Arbour et al., 2017; Hanks et al., 2016; Sigurdardottir et al., 2014; Sela-Kaufman et al., 2013; Dumont et al., 2004). Two studies examined factors related to resilience using qualitative methodology (Arbour et al., 2017; Dumont et al., 2004), and indicated the following factors are related to resilience in the context of TBI: attributing meaning to the TBI, creating a new support system, redefining roles and responsibilities, learning to live with chronic deficits, finding comfort in comparison, adjusting to having more time, realizing resilience potential, adapting to being a changed person, dynamism, perceived self-efficacy, and will. Of the 3 studies that quantitatively examined specific factors related to resilience (Oldenburg et al., 2018; Hanks et al., 2016; Sigurdardottir et al., 2014; Sela-Kaufman et al., 2013), the following were identified: problem-solving coping style, perceived social support, trait positive and negative affectivity, social diversion, control over one's life, sense of mastery, and adaptive premorbid "Big 5" personality traits. Lastly, the study conducted by Sigurdardottir et al. (2014) indicated that participants who did not demonstrate resiliency post-injury were more likely to demonstrate avoidant-focused coping styles, pre- and post-injury substance abuse, and pre- and post-injury psychiatric problems, suggesting potential contribution of such factors to the construct and development of resilience.

Five studies measured the stability of resilience over time. Two such studies showed resilience to be relatively stable across time (Marwitz et al., 2018; Losoi et al., 2015b), 2 studies reported an increase in resilience scores in response to a resilience intervention (Donnelly et al., 2019; Kreutzer et al., 2018), and one study reported clinically meaningful increases in resilience in response to increased productivity over 6-months post-injury (Poritz et al., 2020). Findings among studies that reported on the impact of injury on the stability of resilience were inconsistent. Seven studies indicated that injury history is not significantly associated with resilience levels (Reid et al., 2018; Elliott et al., 2017; Hanks et al., 2016; Losoi et al., 2015a, 2015b; Lukow et al., 2015; Sigurdardottir et al., 2014); however, 3 other studies indicated that a history of TBI is associated with lower resilience (Laird et al., 2019; Kreutzer et al., 2016;

Graham et al., 2013). Furthermore, the study by Graham et al. (2013) indicated a genetic underpinning of low resilience (i.e., serotonin transporter genotype 5-HTTLPR “long” carrier), providing further potential support for at least partial stable trait-like features of resilience.

Relationships Between Reserve and Resilience

The only study included in the current scoping review to examine brain reserve also included analyses of the relationship between brain and cognitive reserve. Kesler et al. (2003) did not find a relationship between cognitive reserve (as measured by estimated premorbid IQ and education level) and brain reserve (as measured by TICV).

Only one study explicitly measured both psychological resilience and cognitive reserve (Hanks et al., 2016). In that study, self-reported resilience was not significantly correlated with estimated premorbid IQ or education, suggesting that resilience and reserve may represent separate constructs. Six studies that focused on resilience included classic proxies of cognitive reserve (e.g., estimated premorbid IQ, education, occupation), but did not explicitly make mention of cognitive reserve. One study that included analyses of resilience and education indicated a significant positive relationship (Kreutzer et al., 2016). A second study that categorized participants based on occupational productivity (i.e., productive: student, homemaker, employed; non-productive: retired, unemployed, volunteer) found productivity to be significantly positively correlated with resilience (Marwitz et al., 2018). Further, this study found education to be positively associated with resilience. Support for a positive association between education and resilience was also provided in the studies by Sullivan et al. (2015) and Sigurdardottir et al. (2014). Lastly, one study found personality traits associated with resilience to be associated with occupational functioning (Sela-Kaufman et al., 2013). However, a study by Rapport, Wong, & Hanks (2019) did not support an association between resilience and estimated premorbid IQ.

Reserve and Resilience as Predictors of Outcome in TBI

Cognitive Reserve

Among the studies included in the current scoping review, cognitive reserve acted as a significant predictor of a number of outcomes of TBI, with all significant relationships demonstrated in the expected direction (i.e., greater cognitive reserve associated with better outcomes). Table 2 details the relationships among proxies of cognitive reserve and specific outcomes following TBI. Overall, higher cognitive reserve was shown to be predictive of better cognitive performance and fewer PCS. However, estimated premorbid IQ was not found to be predictive of depressive symptoms (Wright et al., 2016).

Table 2
Significant relationships reported among proxies of cognitive reserve and TBI outcomes

Proxy	Outcome	Direction of Relationship	Study Authors
Estimated pre-morbid IQ	Cognitive functioning/recovery	Positive	Stenberg et al., 2020; Krch et al., 2019; Fraser et al., 2019; Donders & Stout, 2019; Leary et al., 2018; Steward et al., 2018; Wright et al., 2016; Fuentes et al., 2010; Ropacki & Elias, 2003
	PCS	Negative	Stenberg et al., 2020; Oldenburg et al., 2016; Luis, Vanderploeg, & Curtiss, 2003
Pre-injury IQ[1]	PCS	Negative	Luis, Vanderploeg, & Curtiss, 2003
	Cognitive recovery	Positive	Kesler et al., 2003
Post-injury cognitive ability	PCS	Negative	Fay et al., 2010
Education	Cognitive functioning	Positive	Leary et al., 2018; Kelser et al., 2003
	Neural compensation	Positive	Schiebel et al., 2009
Parental education	Cognitive functioning	Positive	Donders & Kim, 2019
Index of self-reported education, leisure, and occupational functioning	Hospitalization Seizure risk GCS	Negative	Menardi et al., 2020

GCS = Glasgow Coma Scale; PCS = Post-concussive symptoms
[1]Measured pre-injury

Several studies also indicated that cognitive reserve may be a moderator of outcomes of TBI. Estimated premorbid IQ was found to be a significant moderator of the relationship of injury status (i.e., mTBI vs. healthy controls) and injury severity (i.e., mTBI vs. severe TBI) to post-injury cognitive functioning (Stenberg et al., 2020; Krch et al., 2019), with greater effects seen among participants with mTBI in both studies. Estimated premorbid IQ was also found to moderate the relationship between neuropathology and memory performance, with a stronger relationship observed among individuals with lower levels of pathology (i.e., higher fractional anisotropy values; Krch et al., 2019). Premorbid IQ (i.e., measured pre-injury) moderated the impact of loss of consciousness (LOC) associated with the TBI and social support on PCS (i.e., the relationship between presence of LOC and PCS severity was no longer apparent among those with average to high average premorbid IQ; for individuals with above average or below average premorbid IQ, social support was linearly associated with PCS in the expected directions; Luis, Vanderploeg, & Curtiss, 2003). Higher post-injury cognitive ability demonstrated a moderating effect on the relationship between injury and PCS (i.e., individuals with mTBI and lower cognitive ability endorsed greater PCS than those with OI and lower cognitive ability; Fay et al., 2010). Lastly, higher education moderated cognitive performance among children with TBI, such that differences in cognitive performance between children with TBI and healthy children were larger among children with parents of lower education (Donders & Kim, 2019).

Support for cognitive reserve as a protective factor in post-TBI cognitive functioning is mixed and may not extend to all aspects of cognitive functioning or to all populations. Specifically, Donders & Stout (2019) found that, while cognitive reserve (measured by estimated pre-morbid IQ) was positively associated with processing speed, injury severity was a stronger predictor of deficits in processing speed. Further, Fuentes, McKay, & Hay (2010) found measures of cognitive reserve to be associated with only two of six measures of post-injury neuropsychological performance in children with TBI. The study by Leary et al. (2018) did not find a relationship between occupational attainment and neuropsychological outcomes or among estimated pre-morbid IQ, education, or occupational attainment to functional outcomes of TBI. Stenberg et al. (2020) did not find a relationship between cognitive reserve and rate of cognitive recovery. Additionally, estimated premorbid IQ and education, while predictive of a number of neuropsychological outcomes post- mild and moderate TBI, did not predict such outcomes in severe TBI (Stenberg et al., 2020). Parent education was not found to be predictive of processing speed or slowed cognitive tempo among children with TBI (Mahdavi, Hasper, & Donders, 2019). Lastly, Kesler et al. (2003) did not find a relationship between pre- and post-injury IQ.

Brain Reserve

The only study that examined the role of brain reserve in predicting outcomes of TBI indicated that lower TICV was predictive of a greater decline in IQ from pre- to post-injury (Kesler et al., 2003).

Resilience

Resilience was a significant predictor of an array of outcomes following TBI, and the majority of studies demonstrated relationships in the expected direction (i.e., higher resilience associated with better outcomes), with only one study demonstrating effects in the opposite direction. Table 3 lists the outcomes associated with higher resilience in TBI. Overall, resilience was found to be associated with improved psychological, physical, behavioural/adaptive, and social outcomes, as well as PCS. Further, a significant relationship of resilience to social participation and satisfaction was moderated by emotional distress (i.e., stronger positive relationship of resilience to social participation and satisfaction among those with low to moderate levels of distress versus high distress; Vos et al., 2019).

Table 3

Significant relationships reported among resilience and TBI outcomes

Outcome	Direction of Relationship	Study Authors
	Psychological	
Depressive symptoms	Negative	Laliberte Durish et al., 2019; Sima et al., 2019; Laliberte Durish et al., 2018b; Marwitz et al., 2018; Arbour et al., 2017; Elliott et al., 2017; Losoi et al., 2015b; Lukow et al., 2015; Sigurdardottir et al., 2014
Anxiety symptoms	Negative	Laliberte Durish et al., 2019, Sima et al., 2019; Laliberte Durish et al., 2018b; Marwitz et al., 2018; Kreutzer at al., 2016; Sigurdardottir et al., 2014
Post-traumatic stress	Negative	Reid et al., 2018; Elliott et al., 2017; Losoi et al., 2015b; Merritt et al., 2015
Psychological distress	Negative	Vos et al., 2019; Kreutzer et al., 2018; Lukow et al., 2015
Stress	Negative	Kreutzer et al., 2018; McCauley et al., 2013
Subjective overall mental health	Positive	Rapport, Wong, & Hanks, 2019
Emotional distress tolerance	Positive	Elliott et al., 2017
Psychological flexibility	Positive	Elliott et al., 2017
Psychiatric problems	Negative	Sigurdardottir et al., 2014
Affective balance	Positive	Laird et al., 2019
Quality of life/satisfaction with life	Positive	Rapport, Wong, & Hanks, 2019; Sima et al., 2019; Laliberte Durish et al., 2018b; Marwitz et al., 2018; Elliott et al., 2017; Losoi et al., 2015b;
	Physical	
Sleep problems/fatigue	Negative	Elliott et al., 2017; Losoi et al., 2015a, 2015b
Disability	Negative	Rapport, Wong, & Hanks, 2019; Marwitz et al., 2018
Objective physical health	Positive	Rapport, Wong, & Hanks, 2019
	Behavioural/Adaptive	
Adaptability	Positive	Kreutzer et al., 2018; Lukow et al., 2015
Behavioural problems	Negative	Laliberte Durish et al., 2018b
Employment/occupational functioning	Positive	Laird et al., 2019; Sima et al., 2019; Sigurdardottir et al., 2014; Sela-Kaufman et al., 2013
Health-promotive behaviours	Positive	Elliott et al., 2017
Productivity	Positive	Poritz et al., 2020
Substance abuse problems	Negative	Sima et al., 2019
	Social	
Social/community integration and participation	Positive	Rapport, Wong, & Hanks, 2019; Vos et al., 2019; Marwitz et al., 2018; Sherer et al., 2015; Dumont et al., 2004
	Other	
PCS	Negative	Laliberte Durish et al., 2019, 2018a; Oldenburg et al., 2018; Reid et al., 2018; Losoi et al., 2016, 2015b; Merritt et al., 2015; Sullivan et al., 2015; McCauley et al., 2013

PCS = Post-concussive symptoms

Only one study demonstrated a paradoxical association of resilience with outcome, in that higher resilience, while associated with fewer PCS and lower stress at 1-week post-injury, was also associated with greater anxiety and PCS at 1-month post-injury (McCauley et al., 2013). The authors speculate possible explanations for this paradoxical finding to be that one month may not be sufficient time to demonstrate post-traumatic growth, or that missing mediator variables, such as social factors, may have accounted for these effects.

One study commented on the rate of resilience among participants and found that the vast majority of participants demonstrated resiliency (73.5%), defined as low scores on an emotional distress measure across all time points (i.e., 3 months, 1 year, 5 years) following TBI, which acted as a buffer against negative outcomes (Sigurdardottir et al., 2014).

Discussion

The current scoping review aimed to collate the published research examining cognitive reserve, brain reserve, and psychological resilience among individuals with a history of TBI. Broadly, the results support the roles of reserve and resilience as protective factors that buffer negative cognitive, physical, psychological, and social outcomes of all severities of TBI in both children and adults. However, a relative paucity of research focuses on the role of reserve and resilience in pediatric TBI (8 of 47 included studies), and only one published study met the criteria for the current scoping review with respect to the role of brain reserve in TBI.

An array of measures have been used as proxies of reserve and resilience in TBI. Most research supported the use of specific measures of cognitive reserve and resilience, such as estimated premorbid IQ measures (e.g., WTAR, NART) and self-report resilience-specific measures (e.g., CD-RISC). Education and occupation are less applicable as proxies of cognitive reserve in pediatric populations, given that children generally have not completed their education and are not yet employed. Other measures of estimating premorbid IQ (e.g., reading ability) that are used in adults with TBI lack support as valid proxies of cognitive reserve in children (e.g., Fuentes, McKay, & Hall, 2010). Alternatively, post-injury cognitive ability/IQ and parental education may serve as appropriate proxies for children (e.g., Donders & Kim, 2019; Fay et al., 2010). However, post-injury cognitive ability may reliably estimate pre-morbid functioning only in the context of mTBI, given the potential impact of moderate to severe TBI on IQ (Arroyos-Jursdo et al., 2006; Lindgren et al., 1998).

One goal of the current review was to investigate the stability of reserve and resilience and their amenability to modification. While the stability of cognitive reserve was not explicitly measured in the included studies, a number of studies supported the robustness of classic proxies of cognitive reserve to the effects of brain injury, with some exceptions (e.g., Mahdavi, Hasper & Donders, 2019; Steward et al., 2018; Ropacki & Elias, 2003). Specifically, measures of estimated premorbid IQ, education, and occupation were found to be impacted by TBI severity, pointing to potential confounds in the measurement of cognitive reserve in this population. Nonetheless, in keeping with existing theories of cognitive reserve as a dynamic factor impacted by both enrichment and adversity (e.g., Bigler & Stern, 2015), some research included in the current review supports the conceptual understanding of cognitive reserve as a dynamic construct impacted by premorbid psychosocial and environmental factors that may serve to impact neuronal functioning, quality of education, and lifetime enrichment opportunities. Specifically, factors that serve to impact cognitive functioning, such as continued education or substance abuse, may have lasting impacts on cognitive reserve in the context of TBI, as demonstrated by Ropacki & Elias (2003). Such findings demonstrate the dynamic nature of cognitive reserve, and thus, potential modifiability through intervention. Given the positive effects of cognitive reserve on outcomes of TBI reported herein, combined with existing research supporting the effect of increased leisure activity on postmorbid cognitive functioning (e.g., Scarmeas et al., 2001), more research is needed to investigate interventions associated with improving cognitive reserve in individuals with TBI. Such efforts will serve to better elucidate the modifiability of reserve in a

TBI population, and potentially point to methods for improving outcomes for individuals with a history of TBI.

Support for cognitive reserve as a dynamic factor raises concerns regarding reliability of the measurement of cognitive reserve. Given that measurement of cognitive reserve is typically conducted in a post-injury, cross-sectional manner, unitary proxies may not predict past or future responses to TBI, or reliably capture an individual's total reserve. For example, a child who is deemed as having high cognitive reserve based on high parental education could experience events throughout adolescence that impede achievement in school, engage in substance abuse, or experience a neurological event that negatively impacts cognitive functioning. Such experiences could negatively impact education level, occupational attainment, and even reading ability, which would be reflected in the measurement of cognitive reserve in adulthood. As such, reliance on a single proxy measure of cognitive reserve, such as estimated pre-morbid IQ, at a single time point, may not reliably capture an individual's overall reserve. That is, impacts of having been raised in an enriched environment from highly-educated parents may not be captured by a single proxy of cognitive reserve in adulthood, and therefore may lead to erroneous assumptions regarding the prediction of future outcomes. Thus, given support for the negative effects of TBI severity on reliability of estimated premorbid IQ (e.g., Steward et al., 2018) as well as contradictory findings associated with the use of certain proxies of cognitive reserve in a TBI population (e.g., Leary et al., 2018; Fuentes, McKay, & Hall, 2010), cognitive reserve may be best captured in a multifactorial manner. Levi et al. (2013) reported that a three-factor model, including measurement of premorbid SES, estimated premorbid IQ, and premorbid leisure activity, was the best predictive model of cognitive reserve. Such findings are consistent with theoretical support for a multidimensional and dynamic model of cognitive reserve, impacted by a number of environmental, genetic, and individual variables (e.g., see Bigler & Stern, 2015), and may therefore represent a more reliable manner of capturing cognitive reserve. For example, the study by Menardi et al. (2020) included a self-report cognitive reserve questionnaire (Cognitive Reserve Index questionnaire) that captured education, working activity, and leisure activity. Such multidimensional measures may represent a more cohesive and reliable method of measuring cognitive reserve.

Studies of resilience in TBI provide ample evidence that resilience is a dynamic construct amenable to change post-injury (e.g., Poritz et al., 2020; Donnelly et al., 2019; Kreutzer et al., 2018). Furthermore, interventions aimed at increasing resilience appear to have a positive effect on TBI-associated outcomes, supporting the modifiability and positive impact of resilience (Donnelly et al., 2019; Kreutzer et al., 2018). While a number of studies indicate resilience levels are unlikely to be affected by the injury itself, a few other studies offer evidence to the contrary (e.g., Laird et al., 2019; Kreutzer et al., 2016; Graham et al., 2013). Nonetheless, while resilience may be altered by the impact of injury, Sigurdardottir et al. (2014) found that demonstrations of resiliency may be common among individuals with TBI. Such findings fit with notions in resiliency theory suggesting that resiliency is not a rare phenomenon, but is demonstrated in different ways by the majority of individuals (Masten et al., 2009).

Research discussed herein supports existing theoretical conceptualizations linking cognitive and brain reserve to active and passive models of reserve, respectively (e.g., Steward et al., 2018; Kelser et al., 2003). Specifically, support was provided for the presence of active compensatory and efficiency mechanisms of cognitive reserve (Schiebel et al., 2009; Steward et al., 2018), and a passive threshold mechanism of brain reserve (Kelser et al., 2003). However, study findings were conflicted with regards to clarity surrounding neural compensation versus efficiency as mechanisms underlying cognitive reserve in the context of TBI. That is, while Schiebel et al. (2009) supported a compensatory model of cognitive reserve by demonstrating compensatory neural network engagements involved in the completion of cognitive tasks, Steward et al. (2019) found support for efficiency of existing neural networks among individuals with high cognitive reserve. Thus, future research efforts should be directed towards elucidating the neural mechanisms underlying cognitive reserve in the context of TBI.

The current review indicates that reserve and resilience represent distinct, though potentially related, constructs in the context of TBI. The relationship between cognitive reserve and resilience has the strongest support, albeit depending on the proxies used to capture cognitive reserve. Several resilience-focused studies that included measures of classic proxies for cognitive reserve provided support for positive correlations between resilience and education (e.g., Marwitz et al., 2018, Kreutzer et al., 2016, Sullivan et al., 2015), as well as occupation (Marwitz et al., 2018; Sela-Kaufman et al., 2013). Given robust support for the use of education and occupational attainment as proxies of cognitive reserve in adults with TBI (e.g., Stern et al., 1992; Stern, 2003; Richards & Sacker, 2003), these positive associations can be taken to represent at least partial support for a relationship between resilience and cognitive reserve. However, several studies did not find a relationship between resilience and estimated premorbid IQ (e.g., Rapport, Wong, & Hanks, 2019; Hanks et al., 2016). Moreover, cognitive reserve, as measured by estimated premorbid IQ, may not be associated with brain reserve, as measured by TICV, although this conclusion is based on findings from only a single study (i.e., Kesler et al., 2003). Future studies aimed at examining the relationships among cognitive reserve, brain reserve, and psychological resilience might better inform a more cohesive model of resilience and reserve among individuals with TBI.

Limitations

A limitation of the current scoping review was the reliance on a single reviewer for study selection and data abstraction. Thus, the reliability of the literature review process is less certain than if a second reviewer had been included. Additionally, more extensive literature exists that examines reserve and resilience across a broader acquired brain injury population (e.g., stroke, brain tumor, encephalopathy). Such studies were not included in the current review, limiting the scope of the review and generalizability of conclusions. Further, definitions of reserve and resilience vary among researchers (e.g., intelligence, SES, white matter integrity, hardiness, post-traumatic growth), and only those studies that specifically mentioned brain or cognitive reserve or resilience were included in the current review; thus, the findings may be limited in scope.

Conclusions and Future Directions

In conclusion, the bulk of the published research examining the roles of reserve and resilience in individuals with a history of TBI indicate that such factors are associated with improved outcomes. Several gaps in the literature were identified within the current review. First, relatively few studies have examined the role of brain reserve in the context of TBI. Second, more research is needed to better understand appropriate proxies of reserve in children. Relatedly, research is needed to construct a developmental model of reserve in children to better elucidate how and when reserve is best measured, as well as the impact of development on reserve among children. Third, future studies should utilize multidimensional models of cognitive reserve in order to reliably capture this construct in individuals with TBI. Fourth, research is needed to clarify mechanisms of cognitive reserve in TBI (i.e., neural reserve vs. compensatory models). Fifth, less research has been directed to understanding differences in the roles of reserve and resilience across different severities of TBI. For example, only 4 studies explored the role of cognitive reserve among mild TBI, whereas 13 studies explored the role of resilience in mild TBI. The results of this research are unclear as to whether the impacts of cognitive reserve and resilience differ among different TBI severity levels. Therefore, future studies should investigate differential roles of reserve and resilience in different severities of

TBI. Lastly, existent research should guide future studies aimed at exploring interventions with the goal of improving resilience and development of reserve in individuals with TBI.

Study 2

Predicting Trajectories of Post-Concussive Symptoms in Children with Concussion and Orthopaedic Injury: The Roles of Psychological Resilience, Cognitive Reserve, and Brain Reserve

Introduction

Pediatric Concussion

Concussion is defined as an injury to the brain sustained through biomechanical forces resulting in functional disturbance (McCrory et al., 2017). While the term "concussion" is often used interchangeably with "mild traumatic brain injury" (mild TBI), concussion represents the most minor severity along the spectrum of TBI and does not result in identifiable structural changes to the brain (i.e., no imaging abnormalities on CT/MRI) (McCrory et al., 2017). Concussion is a common injury among children and youth. Half a million children under the age of 14-years present to the emergency department with concussion each year in the United States (Bazarian et al., 2005). Furthermore, concussions account for approximately 1.1 to 1.9 million sports- and recreation-related injuries, annually, in children under the age of 18 years (Bryan et al., 2016). Although alarming, these statistics are likely an underestimate of true prevalence rates, as many concussions go unreported. Concussion in children and youth has become a substantial public health burden, accounting for more than $1 billon in health care costs each year in the United States, which, at a population level, accounts for 75-88% greater costs than moderate or severe TBI (Graves, Rivara, & Vavilala, 2015). The complex pathological processes involved in concussion have gained widespread attention from researchers, but continue to be only minimally understood, particularly with respect to the developing brain.

Outcomes of Pediatric Concussion

A number of physical, cognitive, and psychological outcomes are associated with concussion in children, both in the acute and long-term phases of recovery. Immediately following injury, common symptoms include headache, dizziness, nausea, irritability, increased worry, fatigue, sleep problems, attention difficulties, and difficulty concentrating. These symptoms are referred to as post-concussive symptoms (PCS) and are usually present throughout the duration of recovery (Ryan & Warden, 2003). Approximately 77% of children suffer from PCS within the first week following injury, and 32% remain symptomatic at 1-month post-injury (Eisenberg, Meehan, & Mannix, 2014). Presence of ongoing PCS at 1-month post-injury negatively impacts both physical- and psychosocial-related quality of life in children and adolescents (Howell et al., 2019). The majority of children who sustain a concussion recover from PCS within approximately 3-months post-injury (Barlow et al., 2010); however, a significant minority, ranging from 10-30%, will go on to experience persistent symptoms that can last far beyond this expected recovery period (Yumul et al., 2020; Eisenberg, Meehan, & Mannix, 2014; Barlow et al., 2010). PCS hamper return to school and sport (Rose, McNally, & Heyer, 2016; Grubenhoff et al., 2015), resulting in further detrimental effects on psychosocial functioning, and are therefore important to mitigate. Furthermore, consensus on long-term outcomes of concussion in terms of PCS is mixed. The vast majority of literature in the area of pediatric concussion indicates favourable outcomes within several months of injury (Hung et al., 2014), yet a number of studies have been increasingly focused on attempting to better understand the subset of children (i.e., 1 in 7; Barlow et al., 2010) that experience persistent symptoms long after expected recovery. In particular, researchers have attempted to better understand the contribution of both injury and non-injury factors that contribute to acute and persistent PCS.

Injury and Non-Injury Predictors of Outcome

Injury-related factors refer to neuropathological processes involved in sustaining an injury to the brain (Barkhoudarian, Hovda, & Giza, 2011), whereas non-injury-related factors refer to individual or environmental correlates, both pre- and post-injury, that can affect outcomes (Yeates et al., 2009). Injury severity is one important injury-related factor often used to predict outcomes (McNally et al., 2013). Several proxies are commonly used to indicate injury severity, including loss of consciousness, post-traumatic amnesia, and/or vomiting around the time of injury, as well as neuroimaging findings related to the injury, such as contusion or edema (Olsson et al., 2013; Yeates et al., 2012; Taylor et al., 2010). Studies show that children with worse concussion severity, sometimes labelled as complicated mild TBI, are more likely to experience greater levels of PCS (Taylor et al., 2010), despite the fact that their injury is still classified as “mild” in nature. Other injury-related factors, such as headache or loss of consciousness around the time of injury, can also predict the risk of increased PCS (Babcock et al., 2013; McNally et al., 2013), though these factors are generally limited to predicting outcome in the acute phase of recovery. In addition to injury related factors, a number of non-injury factors are also predictive of outcome following concussion, which can be further broken down into interpersonal and environmental factors, both pre- and post-injury.

The finding that PCS are non-specific to TBI, but are also seen in healthy or non-head injured controls (e.g., orthopaedic injury; OI) (Yeates et al., 2009), has provided support for the idea that non-injury factors are likely related to the presence of persistent PCS. Non-injury interpersonal factors that predict greater PCS include female sex and adolescent age at the time of injury (Taylor et al., 2010), poor coping skills (Woodrome et al., 2011), pre-morbid learning and psychiatric problems (Ponsford et al., 1999), and pre-morbid symptoms and behavioural adjustment problems (Yeates et al., 2012). Additionally, a number of environmental and external risk factors have been identified as contributors to increased PCS, including lower socioeconomic status (SES) (Taylor et al., 2010) and poorer parental psychological adjustment (McNally et al., 2013). Evidence for the contribution of non-injury risk factors to PCS provides a basis for researchers to examine the role of intervention efforts to modify such factors and, thus, improve outcomes. However, the progression of this research has been slowed by a tendency to examine injury and non-injury factors separately. Clearly, outcomes related to concussion in children stem from complex, interrelated biopsychosocial processes. Therefore, such factors should be examined from a unified perspective, combining neurobiological and psychological factors into one model to capture their interrelatedness, rather than studying them as individual components. Furthermore, while a relative dearth of literature exists on non-injury risk factors associated with concussion outcomes in children, even fewer studies exist with respect to the role of protective factors, such as reserve and resilience, which are important to elucidate to better differentiate between children with good versus poor outcomes.

Predicting Wellness After Concussion

The lens of medical research is often focused on identifying factors related to problems in functioning, with the ultimate goal of improving the prediction of individual prognosis. Advancements in the identification of risk factors has no doubt been integral to identifying appropriate interventions aimed at mitigating barriers to optimal functioning following concussion (Conder & Conder, 2015). However, along with the positive psychology movement has come a growing interest in studying factors related to improved outcomes of illness and injury, including concussion (e.g., Beauchamp et al., 2019). Research is increasingly shifting away from merely examining factors that lead to increased problems in functioning to make way for a better understanding of adaptation and recovery following adverse events in an effort to harness factors that promote wellness. Positive psychology represents a shift in the perspective taken to understand human behavior, with the goal of examining wellness rather than disorder. Positive psychology does not necessarily refer to the absence of disease or disorder, but instead refers to exploring factors that are related to optimal functioning (Seligman & Csikszentmihalyi, 2000). Factors related to positive psychology that have been shown to be predictive of positive outcomes following TBI include positive affect (Williams et al., 2014), optimism (Ramanathan et al., 2011), and resilience (Kreutzer et al., 2016; Lukow et al., 2015; Laliberté Durish et al., 2018; 2019). While strong evidence exists to suggest the importance of understanding predictors of wellness, efforts to examine predictors of wellness following concussion are relatively limited. A growing interest in the role of protective factors, such as psychological resilience, cognitive reserve, and brain reserve, has led researchers to investigate their roles in predicting wellness in the context of a number of neurological conditions, including TBI and concussion (Dekhtyar et al., 2015; Stern, 2012; Fay et al., 2010; Kesler et al., 2003). However, resilience and reserve factors are only minimally understood in the context of pediatric concussion.

Psychological Resilience

A prominent focus in the positive health psychology literature is the role of resilience in predicting improved outcomes for individuals suffering adverse health events. Resilience is a broad concept that encompasses interpersonal, social, and communal factors associated with positive adaptation in response to adversity (Southwick et al., 2014). While the broad conceptualization of resilience is important in understanding nuances related to improved functioning, psychological resilience, defined as a process involving harboring interpersonal qualities that enable positive adaptation following adversity (Connor & Davidson, 2003), in particular has been shown to be modifiable through intervention (Sullivan et al., 2015). Studying modifiable predictors of wellness following injury is an important research target to guide interventions towards improved outcomes for children with a history of concussion.

Research on the relationship between psychological resilience and PCS is scarce, particularly with respect to pediatric populations. Limited existing research generally supports a negative association, suggesting that higher resilience is predictive of fewer PCS (Laliberté Durish et al., 2018, 2019; Losoi et al., 2015; Sullivan et al., 2015; Merritt et al., 2015). Furthermore, adult mild TBI patients with high resilience have been found to report fewer PCS than those with low resilience as long as 12 months post-injury (Losoi et al., 2015), and the relationship of resilience to PCS has been shown to exist over and above other relevant factors such as age, history of injury, and education (Sullivan et al., 2015). Only two studies examining the relationship between resilience and PCS in pediatric concussion have been published to date (Laliberté Durish et al., 2018; Laliberté Durish et al., 2019). Both studies support a negative relationship between psychological resilience and PCS. However, several shortcomings related to small sample sizes, cross-sectional nature of the study designs, and absence of pre-injury symptom ratings, as well as limited generalizability of the sample (i.e., consisting of patients presenting to a concussion clinic on the basis of poor recovery), limit the study conclusions. Thus, a prospective longitudinal design with a larger, more generalizable sample that accounts for pre-injury symptoms is needed to better capture and describe this relationship. Nonetheless, such findings provide promising support for identifying modifiable factors related to the prediction of improved outcomes following concussion.

While the specific application of psychological resilience theory to concussion is a recent contribution to the literature, examining factors that buffer the effects of injury or illness is not new to the field of neurology. Researchers have long been interested in the concept of reserve as a protective factor against the detrimental effects of brain injury (e.g., Stern, 2012), though the theory has been only minimally explored in the context of pediatric concussion.

Reserve

Cognitive Reserve

Cognitive reserve has been proposed as a mechanism by which to explain individual differences in outcome of neurological disease and injury (Stern, 2003; 2012). The theory of cognitive reserve posits that individuals with greater neural efficiency or compensatory ability, as a result of higher intelligence (IQ) or exposure to more enriching environments, are better able to maintain functioning despite neurological adversity. Cognitive reserve is generally captured by measuring proxies of IQ and environmental enrichment, such as estimated pre-morbid IQ, education, occupational functioning, and social/leisure functioning (Bennett et al., 2006; Stern, 2003; Richards & Sacker, 2003; Scarmeas et al., 2001; Alexander et al., 1997; Stern et al., 1994; Stern et al., 1992). To date, a relative paucity of research has been dedicated to examining the role of cognitive reserve in TBI, particularly concussion, and even fewer published studies have examined this relationship in a pediatric population. One study, conducted by Fay and colleagues (2010), found cognitive reserve, as measured by a composite score of cognitive ability (i.e., the average of standard scores on a battery of neurocognitive measures), to be a moderator of PCS in children with complicated mild TBI (i.e., mild TBI associated with lesions visible on neuroimaging). That is, children with complicated mild TBI were more likely to suffer PCS, as compared to children with OI, if they had lower cognitive ability. Further support for the role of cognitive reserve as a moderator of outcomes in pediatric TBI was provided by a study conducted by Donders & Kim (2019), who found parental education (used as a proxy of cognitive reserve) to moderate cognitive functioning among children with a history of various severities of TBI. However, support for the role of cognitive reserve as a predictor or moderator of outcome is inconsistent (e.g., Mahdavi, Hasper, & Donders, 2019). In adults with concussion/mild TBI, lower cognitive reserve, as measured by estimated premorbid IQ, education, and occupational attainment, was found to be predictive of persistent (i.e., > 3 months) PCS (Oldenberg et al., 2016). Higher cognitive reserve has also been found to be predictive of broad cognitive outcomes following TBI (Stenberg et al., 2020; Donders & Stout, 2019). Taken together, research on the topic of cognitive reserve and concussion, although sparse, indicates greater reserve to be associated with better outcomes. However, the scarcity of studies examining this relationship in the context of pediatric concussion points to a need for further research.

Brain Reserve

Similar to cognitive reserve, brain reserve is proposed as a protective factor that accounts for variability in outcome following neurological injury or disease, by means of physiological threshold (Satz, 1993). Brain reserve theory posits that larger brains are more resilient to insult on the basis of higher neuronal count. Brain reserve is typically quantified by measuring brain volume (i.e., whole brain volume or total intracranial volume; Bigler, Johnson, & Blatter, 1999). A review of the literature suggests that studies examining the direct relationship between brain volume and outcomes of concussion are extremely scarce in the adult population and non-existent in children. A study by Kelser and colleagues (2003) is the only published study of which we are aware to specifically examine the role of brain reserve in predicting outcomes of TBI, and indicated a positive relationship among total intracranial volume and cognitive outcome following TBI in adults. Grey matter volume, but not whole brain volume, has been found to positively correlate with PCS in adults with concussion/mild TBI, but not controls (da Costa et al., 2016). Nonetheless, the question of whether brain volume as a proxy of brain reserve acts as a buffer against negative effects of concussion in children has yet to be addressed.

Objectives

Overall, existing research on the topic of pediatric concussion has largely focused on examining factors predictive of poor outcomes. Research on resilience and reserve in TBI and concussion, while limited, has mostly examined these factors separately. While theoretical descriptions of resilience and reserve suggest potential overlap in these constructs, previous research examining the relationships among resilience and reserve in TBI is mixed (e.g., Hanks et al., 2016; Kreutzer et al., 2016; Kelser et al., 2003). Overall, such research is limited and therefore provides only a narrow and piecemeal understanding of resilience and reserve in the context of concussion. The paucity of existing research on resilience and reserve in concussion, coupled with the important implications of examining predictors of wellness following pediatric concussion (e.g., Beauchamp et al., 2019), suggests a clear need to examine such factors in this population. Studied in a single model, better understanding the roles of and relationships among resilience and reserve may help to account for at least partial heterogeneity in the prediction of outcomes of pediatric concussion.

The objective of the current study was to examine the roles of psychological resilience, cognitive reserve, and brain reserve, as predictors of acute and persistent PCS among children and adolescents who sustained a concussion or orthopaedic injury (OI). Specifically, the goal of the study was to identify the influence of these factors on symptom trajectories over the course of the first 6-months post-injury, both as main effects and as moderators of group differences. The purpose of including an OI group was to provide a non-head injured comparison while simultaneously controlling for the effect of exposure to medical trauma. Secondary analyses were also completed to examine the correlations among psychological resilience, cognitive reserve, and brain reserve within the sample, with the goal of better understanding the relationships between these constructs and whether or not they differ for children with concussion versus OI.

Three hypotheses were tested: (1) based on previous studies exploring the relationship of psychological resilience, cognitive reserve, and brain reserve to outcomes of TBI, all 3 factors were expected to be negatively associated with PCS scores in both groups across all time points; (2) all three factors were expected to moderate the relationship between injury and PCS, such that the effects of concussion (i.e., greater PCS) would be more pronounced at low levels of psychological resilience, cognitive reserve, and brain reserve; and (3), given previous, albeit limited, support for a positive relationship among resilience and reserve factors (e.g., Kreutzer et al., 2016; Kesler et al., 2003), all three factors were hypothesized to be positively correlated, such that greater psychological resilience would be associated with greater cognitive reserve and brain reserve, with a similar positive relationship observed between cognitive and brain reserve.

Methods

Participants

The current study is a subset of a larger parent project, entitled Advancing Concussion Assessment in Pediatrics (A-CAP; Yeates et al., 2017). The objective of A-CAP is to better understand biopsychosocial predictors of prognosis in children and youth with concussion, as well as to improve diagnosis. Participants (N = 967), ages 8-17 years, and their caregivers, were recruited from emergency departments at five children's hospitals across Canada (Alberta Children's Hospital, Children's Hospital of Eastern Ontario, Ste-Justine Hospital, Stollery Children's Hospital, BC Children's Hospital) after sustaining either a concussion (*n* = 633) or orthopaedic injury (OI; *n* = 334). All participating sites were members of the Pediatric Emergency Research Canada (PERC) network (Bialy et al., 2018). Participants were followed for 6 months post-injury and assessed at 3 different time points: approximately 10-days post-injury (i.e., "post-acute) and 3- and 6-months post-injury. All three assessments included the completion of self- and parent-report measures of PCS. Magnetic resonance imaging (MRI) was completed during the post-acute assessment, and intelligence testing was completed during the 3-month assessment.

Inclusion and exclusion criteria for the A-CAP study are outlined in Table 4. The primary inclusion criterion for the concussion group was sustainment of a head trauma that resulted in at least one of the following three criteria: (1) observed loss of consciousness, (2) a Glasgow Coma Scale (GCS; Teasdale & Jennett, 1974), of 13 or 14, and (3) presence of at least one symptom of concussion (e.g., post-traumatic amnesia, focal neurological deficits, post-traumatic seizure, vomiting, headache, dizziness, or other change in mental status). The primary inclusion criterion for the OI group was sustainment of an upper or lower extremity injury (e.g., fracture, sprain, strain), with an associated Abbreviated Injury Scale (AIS; AAAM, 1990) score of 4 or less. An additional inclusion criterion for both groups was presentation to the emergency department within 48 hours of the injury. Exclusion criteria for the concussion group included signs indicative of more severe TBI (e.g., loss of consciousness lasting more than 30 minutes, post-traumatic amnesia lasting greater than 24 hours, GCS score of less than 13), and any associated injury with an AIS score of greater than 4. Exclusion criteria for the OI group included any injury to the head or symptoms of concussion.

Table 4

Inclusion and exclusion criteria for A-CAP study

	Concussion	OI
Inclusion	A blunt head trauma with at least one of the following injury characteristics: • Lowest GCS score of 13-14 (out of 15) • Observed LOC • At least one reported symptom (e.g., PTA, focal neurological deficits, skull fracture, post-traumatic seizure, vomiting, headache, dizziness, other mental status change) noted by ED medical personnel around the time of injury	• An orthopaedic (i.e., non-head) injury to the thorax, upper extremity and/or lower extremity with Abbreviated Injury Scale Score of 4 or less • Injury related to blunt force/physical trauma
	Both Groups • Presentation to the ED within 48 hours of injury	
Exclusion	• A more severe TBI with the following characteristics: o A GCS score of ≤ 13; o LOC ≥ 30 minutes; or o PTA ≥ 24 hours o Neurosurgical intervention • Associated OI with AIS score > 4	• Any injury requiring surgical intervention or procedural sedation (not excluded for use of analgesic/pain management medication) • Head trauma or symptoms of concussion
	Both Groups • Hypoxia, hypotension, or shock during or following injury (if known) • Non-English-speaking child or parents (non-English and non-French speaking in Quebec and Ottawa) • Previous TBI requiring overnight hospitalization, by parent report • Previous concussion within the past 3 months, by parent report • Previous neurological or neurodevelopmental disorder (e.g., epilepsy, intellectual disability, autism spectrum disorder), by parent report • Hospitalization in the previous year for psychiatric disorder, by parent report • Administration of sedative medication (e.g., Propofol, ketamine, nutrouus oxide, midazolam, benzodiazepines) prior to ED data collection (pain management medications not an exclusion) • Obvious drug or alcohol ingestion associated with injury • Injury-related abuse or assault • Legal guardian not present or child in foster care • Excluded from MRI if child has orthodontic (e.g., braces) or medical contraindications to MRI	

ED = emergency department, OI = orthopaedic injury, GCS = Glasgow Coma Scale, LOC = Loss of consciousness, PTA = Post-traumatic amnesia

Measures

Psychological Resilience

Psychological resilience was measured using the 10-item version of the Connor-Davidson Resilience Scale (CD-RISC; Connor & Davidson, 2003; Campbell-Sills & Stein, 2007), administered during the post-acute assessment. The CD-RISC is the most widely-used self-report measure of resilience, and assesses factors related to resilience such as personal competence, tenacity, tolerance of negative affect, positive acceptance of change, and control (Connor & Davidson, 2003). The 10-item version includes items 1, 4, 6, 7, 8, 11, 14, 16, 17, and 19 from the full, 25-item version and was found to have better factor structure and psychometric properties than the 25-item scale (Campbell-Sills & Stein, 2007). The 10-item CD-RISC has satisfactory validity when used in a pediatric population (Laliberté Durish, Brooks, & Yeates, 2018). Each item is measured on a 5-point scale, from 0 (Not true at all) to 4 (True nearly all the time). Total possible scores range from 0 to 40, with higher scores indicative of greater psychological resilience. Studies have not supported a consistent factor structure for the CD-RISC (Campbell-Sills & Stein, 2007); therefore, only total scores are included in the analyses.

Cognitive Reserve

Full Scale IQ (FSIQ) was measured as a proxy of cognitive reserve using the Wechsler Abbreviated Scale of Intelligence-Second Edition (WASI-II; Wechsler, 1999). FSIQ scores, derived from the 2-subtest short form of the WASI-II (i.e., Vocabulary and Matrix Reasoning), were included in the analyses. The WASI-II is a widely used measure of IQ, and the 2-subtest FSIQ has been shown to have excellent reliability in a pediatric population (McCrimmon & Smith, 2013). The WASI-II was administered during the 3-month follow-up visit to reduce participant burden associated with the post-acute assessment. IQ has been shown to remain relatively stable following concussion (Babikian & Asarnow, 2009); therefore, delaying IQ data collection to 3 months was not thought to impact the use of FSIQ as an estimate of pre-injury cognitive functioning.

Brain Reserve

Brain reserve was measured using total brain volume. All participants completed magnetic resonance imaging (MRI) at the post-acute assessment (i.e., approximately 10-days post-injury).

Acquisition. A total of N = 626 children completed a 3T MRI without sedation at the post-acute assessment. Scans were completed between 1.5 and 32.9 (M = 11.6, SD = 5.4) days post-injury. MRI data was acquired in approximately 45-60 minutes. Three-dimensional T_1-weighted anatomical images were acquired with the site-specific acquisition parameters listed in Table 5.

Quality assurance. All images were inspected for visual artifact by experts who were blind to group membership. Data from 76 participants (concussion n = 57, OI n = 19) were excluded due to poor quality of the T1-weighted data (e.g., severe motion or scanner artifact, reduced field of view/cropped image, wrong acquisition) or incomplete data acquisition (e.g., failure or refusal to complete the MRI). Three participants from the OI group were excluded for incidental findings.

Image preprocessing. Preprocessing and brain extraction procedures were completed on a remote Linux computing cluster at the University of Calgary in Alberta, Canada. T_1-weighted DICOM data were converted into NIfTI format using the dcm2niix tool in MRIcron (publicly available software; https://github.com/rordenlab/dcm2niix). During conversion to NIfTI format, T1-weighted images were automatically reoriented to canonical space and auto-cropped. T1-weighted images were then put into standard alignment using the Automatic Registration Toolbox acpcdetect tool (freely downloadable at https://www.nitrc.org/frs/?group_id=90), and resampled to an isotropic voxel resolution of 1 mm^3 using the Convert3D Medical Image

Processing Tool (freely downloadable at http://www.itksnap.org/pmwiki/pmwiki.php?n=Downloads.C3D).

Total brain volume estimation. Brain extraction and total brain volume were derived using the open source Advanced Normalization Tools version 3.0.0.0.dev13-ga16cc (compiled January 18, 2019) volume-based cortical thickness estimation pipeline (antsCorticalThickness.sh) using the OASIS pediatric template from the MICCAI 2012 Multi Atlas Challenge (Tustison et al., 2014). Total brain volume estimates included cumulative estimates of total cortical and subcortical grey matter, total white matter, cerebrospinal fluid, and cerebellum. Data was harmonized to correct for site differences using ComBAT (Fortin et al., 2018).

Table 5.
3T MRI scan protocols for each of the study sites

	T1-weighted Anatomical Image Acquisition Parameters								
Site	**Scanner**	**Type/ Direction**	**Scan time (min)**	**Resolution[1]**	**Slices**	**FOV (cm^2)**	**TR (ms)**	**TE (ms)**	**TI (ms)**
Calgary Concussion *n*=75 OI *n*=35	GE MR750w	FSPGR BRAVO/ Axial	5:28	0.8 mm^3	226	512 x 512	8.25	3.16	600
Edmonton Concussion n=65 OI *n*=37	Siemens	MP-RAGE/ Sagittal	4:47	0.8 mm^3	192	290 x 320	1880	2.90	948
Montreal Concussion *n*=34 OI n=8	GE MR750	FSPGR BRAVO/ Axial	5:28	0.8 mm^3	192	512 x 512	7.90	3.16	600
	Siemens Prisma	MP-RAGE/ Sagittal	4:47	0.8 mm^3	192	290 x 320	1880	2.90	948
Ottawa Concussion *n*=67 OI *n*=25	Siemens Skyra	MP-RAGE/ Sagittal	4:47	0.8 mm^3	176	256 x 256	2200	2.50	948
Vancouver Concussion *n*=64 OI *n*=57	GE MR750	FSPGR BRAVO/ Axial	5:28	0.8 mm^3	226	512 x 512	7.90	3.16	600

Note. T1-weighted images were collected with a flip angle = 10 degrees
[1]Converted to $1mm^3$

Post-Concussive Symptoms

PCS were measured using the Health and Behaviour Inventory (HBI; Ayr et al., 2009). The HBI is a 20-item self- and parent-report questionnaire that contains items pertaining to the frequency of cognitive and somatic symptoms over the past week. Items are rated on a 4-point Likert scale ranging from “never” to “often”. The HBI was administered at each follow-up (i.e., post-acute, 3-months, 6-months). The self- and parent-report HBI yield a similar 2-factor structure, with scores reflecting cognitive and somatic symptom domains (Ayr et al., 2009; Mittenberg et al., 1997). Both domain scores are included in the analyses for parent and child ratings at each time point. Parents also completed retrospective ratings of pre-injury PCS during the post-acute assessment using the HBI. Cognitive and somatic domain scores for retrospective PCS ratings were included in analyses as covariates to control for pre-injury symptoms.

Procedure

The parent study (i.e., A-CAP) was approved by the University of Calgary Conjoint Health Research Ethics Board. Children who presented to the emergency department at five hospital sites across Canada (i.e., Alberta Children’s Hospital, Children’s Hospital of Eastern Ontario, Ste-Justine Hospital, Stollery Children’s Hospital, BC Children’s Hospital), after sustaining a concussion or OI, were approached by research assistants and invited to participate in the study. Informed consent and assent were obtained from the caregiver and child upon enrollment into the study. Demographic and injury data were collected during the emergency department visit. Children and caregivers attended a post-acute assessment approximately 10-days post-injury, during which they completed MRI, ratings of psychological resilience, as well as ratings of retrospective and current PCS. Participants attended two additional follow-up assessments at 3- and 6-months post-injury. Children and caregivers rated PCS at each follow-up assessment. IQ testing was completed during the 3-month assessment.

Statistical Analyses

Descriptive statistics of the study sample characteristics and all predictor and outcome variables included in the current study, as well as correlational analyses and calculations of group differences on all variables, were conducted using SPSS, Version 26 (IBM, 2019). Correlation analyses were conducted to examine the relationships among psychological resilience, cognitive reserve, and brain reserve, controlling for age and sex. Correlations were calculated for the overall sample, as well as separately for the concussion and OI groups. Within-group correlations were compared using Fisher's *z* to test for significant group differences in the correlations.

Linear mixed model analyses were conducted using Hierarchical Linear Modelling (HLM) Scientific Software, Version 8 (Raudenbush et al., 2019) to examine psychological resilience, cognitive reserve, and brain reserve as predictors and moderators of group differences in trajectories of PCS among children with concussion and OI. Level 1 data included individual PCS ratings over the three assessment time points (i.e., within-subjects/random effects;) and Level 2 data included predictors (i.e., between subjects/fixed effects; group, CD-RISC, FSIQ, TBV) as well as covariates (i.e., age, sex, retrospective HBI cognitive and somatic scores according to the symptom domain being analyzed). HBI cognitive and somatic domain scores for both parent- and child-reports were analyzed separately as dependent variables. All continuous predictor variables were mean centered, and the intercept for time since injury was set at 10-days post-injury (i.e., approximately the post-acute assessment). The following interaction terms were used to examine the moderating role of each of the primary predictors on the relationships of injury type (i.e., concussion vs. OI) to PCS: group x resilience, group x IQ, group x TBV. Analyses were conducted in a pseudo-hierarchical manner, first examining the effect of group and covariates on the intercept and slope, then adding main effects and associated interactions individually for each of the primary predictor variables (i.e., CD-RISC, FSIQ, TBV) to examine the independent contribution of each predictor/interaction to the model, then adding all predictors and only those interactions that were significant in the previous step, and lastly testing the entire model with all covariates, predictors, and interactions. Given that the potential impact of MRI scanner differences on TBV were controlled by harmonizing TBV data using COMBAT, site was not initially entered as a covariate to preserve power and limit potential multicollinearity. However, site was added to the full models in a final step to ensure effects remained significant after controlling for site. Mixed-effects models are a generalization of multivariable regression models, therefore an estimated power analysis was conducted based on a multivariable regression setting indicating the sample size was sufficient to detect small effect sizes. Specifically, a sample size of 465, *p* of 0.05, and 10 predictors allow for statistical power of 80% to detect an effect size of $f^2 = .04$ for the change in R^2 attributable to any one predictor.

Results

Preliminary Analyses

See Figure 2 for an overview of the sample size and attrition. A total of 5846 individuals were approached in the ED and invited to participate in the study, of whom 3169 met eligibility criteria. A total of 967 individuals (633 concussion, 334 OI) agreed to participate and were enrolled in the study. Of the total participants enrolled, 826 completed the post-acute follow-up, 719 completed the 3-month follow-up, and 692 completed the 6-month follow-up. Analyses indicated no significant group differences among those lost to follow-up at the post-acute, 3-month, and 6-month follow-ups on injury group, sex, age, parental education, recruitment site, injury severity (PTA, LOC, GTA), or any of the symptom outcomes (those who did not attend the 6-month follow-up endorsed marginally significantly greater symptoms on the 3-month child-report HBI Cognitive domain; $t(739) = 1.96$, $p = .051$). Significant differences were present between those who did and did not attend the 3- and 6-month follow-ups in race (χ^2 (5) = 21.89, p = .001 and χ^2 (5) = 24.07, p < .001 for 3- and 6-month follow-ups, respectively). Specifically, Indigenous participants were less likely to return for 3- and 6-month assessments than any other racial group in the sample. Additionally, participants with parental education of high school or less were less likely to return for the 6-month follow-up assessment than participants with higher levels of parental education (χ^2 (3) = 13.12, p = .004).

Given that HLM is unable to compute models with missing data on predictor variables and imputation methods are not meant to handle high levels of missing data, the final sample for analyses was restricted to include only those participants with complete data on all predictors and covariates (i.e., CD-RISC, WASI-II FSIQ, TBV, HBI parent report retrospective cognitive/somatic symptoms, age, sex). A total of 465 participants were therefore included in the final analyses. Comparisons among those included in the final analyses versus those not included indicated no significant differences in group, age, sex, SES (median household income, parental education), race, or injury severity. Significant differences were apparent among recruitment sites (χ^2 (4) = 13.17, p = .010), in that participants from the Ottawa site had more missing predictor data than other sites and participants from the Edmonton site had less missing predictor data than other sites. Furthermore, participants with incomplete predictor data (i.e., those not included in the final analyses) reported more symptoms on the child-reported HBI cognitive and somatic domains at both the 3- and 6-month follow-ups (t(518.46) = 2.35, p = .019; t(535.51) = 2.11, p = .035, and t(553.27) = 2.66, p = .027; t(576.07) = 2.19, p = .029, respectively). While this finding appeared confounded with group, given that a significantly greater proportion of participants in the concussion group were from the Ottawa site (χ^2 (4) = 23.08, p < .001), which had more missing predictor data, an ANOVA examining group X predictor missingness interaction effects on the child-rated HBI cognitive and somatic domains was non-significant. The findings therefore indicate the final sample may represent a less severe group in terms of PCS than the original sample. However, effect sizes were small (d = .16 to d = .21), indicating differences were minimal.

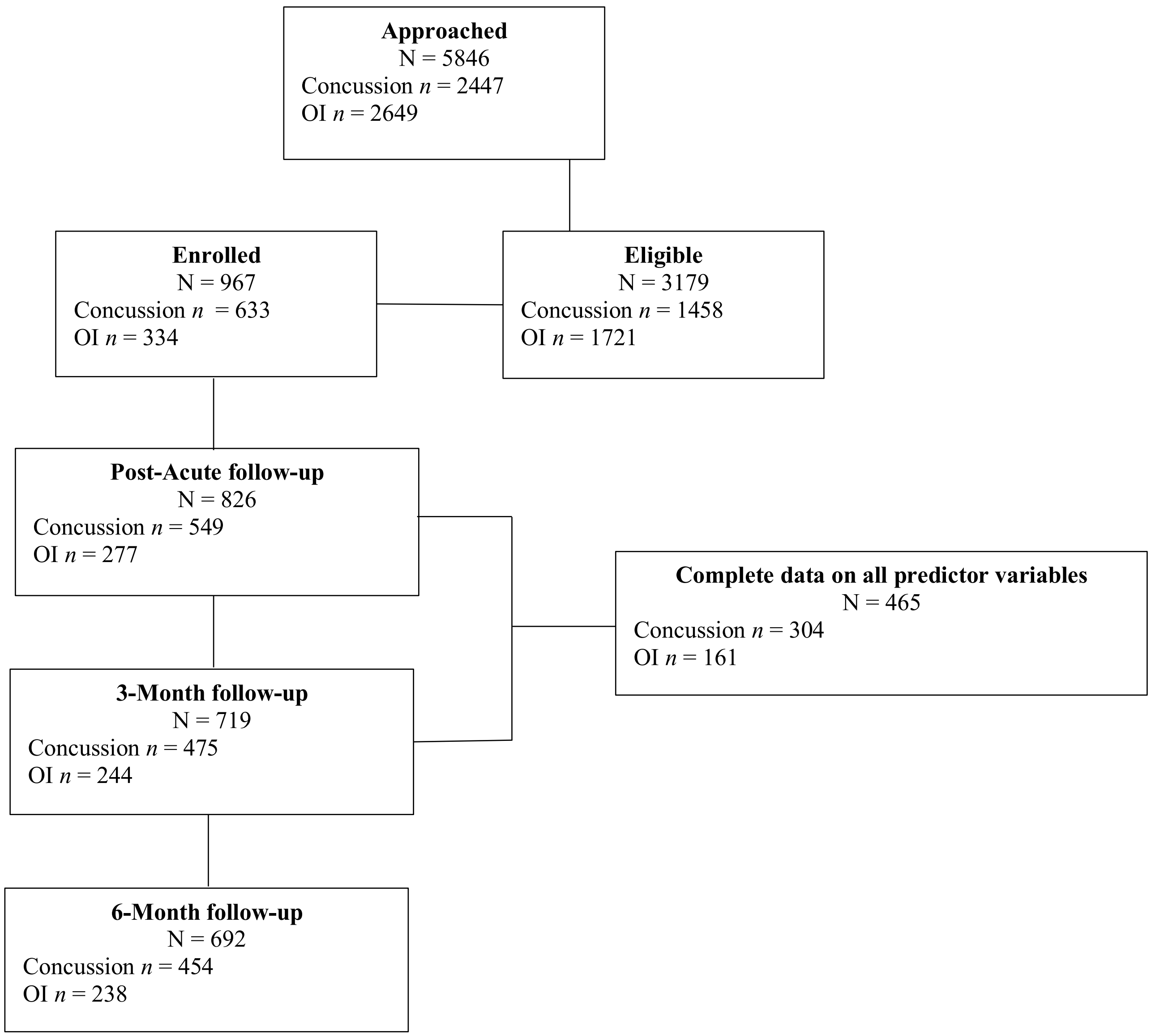

Figure 2. Sample size and attrition.

Group Differences in Sample Characteristics and Study Variables

Demographic and injury characteristics of the study sample are outlined in Table 6. For the overall sample, time since injury ranged from 1 to 54 days at the post-acute follow-up (*M* = 8.0, *SD* = 3.7; aside from one outlier of 54 days, all other cases were ≤ 22 days), 67 to 133 days at the 3-month follow-up (*M* = 94.3, *SD* = 9.8), and 155 to 258 days for at the 6-month follow-up (*M* = 184.5, *SD* = 11.6). No significant group differences (concussion vs. OI) were found in age, race, SES (i.e., maternal education, household income), or time since injury. However, significant group differences in sex were present, with fewer females in the concussion group (37.6% vs. 48.1%; $\chi^2 = 4.88$, $p = .027$, Cramer's V = .10).

Table 6
Sample characteristics

	Concussion	OI	Significance Test		
	***n* = 304**	***n* = 161**	**t/χ^2**	***p***	***d*/V[1]**
Age at Injury			0.86	.388	.08
M (*SD*)	12.3 (2.5)	12.5 (2.3)			
Range	8.0-17.0	8.1-17.0			
Sex			4.88*	.027	.10
% female	37.6%	48.1%			
Race			6.24	.284	.12
% not Caucasian	28.5%	28.4%			
Parental education[3]			0.51	.917	.03
% ≤ High School	15.0%	17.2%			
% Trades/College Degree	31.7%	31.8%			
% University Bachelor's Degree	35.0%	34.4%			
% University Advanced Degree	18.3%	16.6%			
Household Income[4]			-1.29	.198	.13
M (*SD*)	91,855.1 (27,531)	88,615.5 (22,277.9)			
Range	39,366-215,168	41,164-147,903			
Time Since Injury (days)					
Post-Acute Follow-Up			0.79	.432	.08
M (*SD*)	7.9 (4.1)	8.2 (2.7)			
Range	1-54	3-19			
3 Month Follow-Up			0.24	.812	.02
M (*SD*)	94.2 (10.2)	94.4 (9.1)			
Range	68-133	67-129			
6 Month Follow-up			-1.60	.111	.17
M (*SD*)	185.1 (12.3)	183.2 (10.2)			
Range	161-258	155-220			
Injury characteristics[2]					
% experienced LOC	11.1%	-	-	-	-
% experienced PTA	12.7%				
% GCS <15	2.3%				

LOC = Loss of consciousness, PTA = Post-traumatic amnesia
[1] Cohen's *d*; Cramer's V
[2] Concussion group only
[3] Primarily based on maternal education, paternal education where maternal not available
[4] 2016 census track median household income based on postal code

*Significant group differences ($p < .05$)

Descriptive statistics and group differences for primary predictor and outcome variables are presented in Table 7. Analyses of group differences on predictor variables revealed the OI group had a significantly higher WASI-II FSIQ ($t(466) = 2.02$, $p = .044$, $d = .19$). On the two subtests underlying the WASI-II FSIQ score (i.e., Vocabulary, Matrix Reasoning), the OI group performed significantly better on the Matrix Reasoning subtest ($t(466) = 2.61$, $p = .009$, $d = .25$), but not on the Vocabulary subtest. Additionally, participants in the OI group endorsed significantly higher scores on the CD-RISC ($t(466) = 4.75$, $p < .001$, $d = .47$). Notably, effect sizes for the group difference on the WASI-II FSIQ and Matrix Reasoning subtest were small, while the effect size for the group difference on the CD-RISC was medium.

Group differences on PCS were significant for the parent-reported HBI (both the cognitive and somatic domains) at all time points, with exception of the HBI somatic domain at the 6-month follow-up (see Table 7). All group differences were in the expected direction, with parents in the concussion group reporting worse symptoms than those in the OI group. Effect sizes for group differences ranged from medium to large on the post-acute parent report HBI ($d = .70$ for the cognitive domain and $d = 1.32$ for the somatic domain, respectively), with smaller effect sizes observed at the 3- and 6-month follow-ups ($d = .22$ to $d = .32$), which were similar in magnitude to the retrospective ratings ($d = .26$ to $d = .29$). On the child-reported PCS ratings, significant group differences were present on the HBI cognitive domain only at the post-acute follow-up, but significant group differences were found on the HBI somatic domain score at all time points (see Table 7). Again, all group differences were in the expected direction, with the concussion group reporting worse symptoms than the OI group. Large effect sizes were present for group differences on the child-report post-acute HBI domains ($d = 1.04$ and $d = 1.54$ for the cognitive and somatic domains, respectively), with smaller effect sizes present at the other occasions (*d* = .27 to *d* = .29).

Table 7
Descriptive statistics and group differences on predictor and outcome variables

	Concussion	OI	Significance Test		
	***n* = 304**	***n* = 161**	***t***	***p***	***d***
Predictors					
WASI-II					
FSIQ			2.02*	.044	.19
M (*SD*)	105.9 (13.8)	108.5 (12.9)			
Range	64-143	75-142			
Vocabulary (T score)			.075	.455	.07
M (*SD*)	54.2 (8.8)	54.8 (8.6)			
Range	28-80	29-78			
Matrix Reasoning (T score)			2.61*	.009	.25
M (*SD*)	52.7 (9.8)	55.1 (9.2)			
Range	26-76	33-78			
CD-RISC			4.75*	< .001	.47
M (*SD*)	25.0 (7.4)	28.3 (6.7)			
Range	6-40	10-40			
TBV (millions mm^3)[1]			-1.05	.294	.10
M (*SD*)	1.492 (0.128)	1.479 (0.122)			
Range	1.129-1.946	1.182-1.801			
Outcomes (Parent Report)					
HBI Cognitive Retrospective			-2.92*	.004	.29
M (*SD*)	9.4 (7.8)	7.2 (7.1)			
Range	0-31	0-29			
HBI Somatic Retrospective			-2.63*	.009	.26
M (*SD*)	2.9 (3.9)	2.0 (2.9)			
Range	0-26	0-16			
HBI Cognitive Post-Acute			-7.50*	< .001	.70
M (*SD*)	11.7 (8.1)	6.4 (6.9)			
Range	0-33	0-31			
HBI Somatic Post-Acute			-15.50*	< .001	1.32
M (*SD*)	6.9 (5.4)	1.4 (2.3)			
Range	0-27	0-14			
HBI Cognitive 3M			-2.47*	.014	.25
M (*SD*)	7.9 (7.1)	6.2 (6.5)			
Range	0-30	0-26			
HBI Somatic 3M			-3.29*	.001	.32
M (*SD*)	3.0 (3.9)	1.9 (2.8)			
Range	0-24	0-16			
HBI Cognitive 6M			-2.06*	.040	.22
M (*SD*)	7.7 (7.1)	6.2 (6.7)			
Range	0-32	0-26			
HBI Somatic 6M			-1.36	.173	.15
M (*SD*)	2.5 (3.6)	2.0 (2.9)			
Range	0-22	0-13			

Outcomes (Child Report)					
HBI Cognitive Post-Acute			-11.34*	< .001	1.04
M (*SD*)	13.4 (8.1)	6.1 (5.7)			
Range	0-31	0-25			
HBI Somatic Post-Acute			-17.19*	< .001	1.54
M (*SD*)	9.7 (5.7)	2.7 (3.0)			
Range	0-24	0-16			
HBI Cognitive 3M			-1.61	.108	.15
M (*SD*)	7.1 (7.6)	6.0 (6.6)			
Range	0-31	0-32			
HBI Somatic 3M			-3.31*	.001	.29
M (*SD*)	4.4 (5.1)	3.1 (3.6)			
Range	0-25	0-18			
HBI Cognitive 6M			-0.63	.529	.07
M (*SD*)	6.8 (7.5)	6.3 (6.7)			
Range	0-28	0-26			
HBI Somatic 6M			-2.98*	.003	.27
M (*SD*)	4.2 (5.0)	3.0 (3.6)			
Range	0-25	0-20			

CD-RISC = Connor-Davidson Resilience Scale 10-item (total raw score); HBI = Health and Behaviour Inventory (subscale raw scores); TBV = Total brain volume; WASI-II FSIQ = Wechsler Abbreviated Scale of Intelligence – Second Edition Full Scale Intelligence Quotient (standard score)
[1] Harmonized data
*Significant group difference ($p < .05$)

Linear Mixed Models

Table 8 summarizes the significant findings from the full HLM models with all covariates, predictors, and interactions entered into the model, predicting the intercept and slope for each of the outcome variables.

Table 8
Summary of HLM analyses (full models)

		Significant Predictors		
		Predictor	**Coefficient**	***p*-value**
HBI Cognitive (Parent)	Intercept	Pre-injury cognitive symptoms	0.71	<.001
		Resilience	-0.13	.037
	Slope	Pre-injury cognitive symptoms	-0.001	<.001
HBI Somatic (Parent)	Intercept	Age	0.21	.005
		Pre-injury somatic symptoms	0.56	<.001
	Slope	Pre-injury somatic symptoms	-.001	<.001
HBI Cognitive (Child)	Intercept	Sex	-2.34	<.001
		Age	0.53	<.001
		Resilience	-0.26	<.001
	Slope	-	-	-
HBI Somatic (Child)	Intercept	Sex	-1.77	<.001
		Pre-injury somatic symptoms	0.39	<.001
		Resilience	-0.11	.023
	Slope	-	-	-

HBI = Health and Behaviour Inventory

Parent HBI Cognitive Domain

When group (concussion vs. OI) and covariates (i.e., age, sex, pre-injury cognitive symptoms) were examined together, without primary predictor variables entered into the equation, significant effects of group and retrospective pre-injury cognitive symptoms were found for the intercept and slope for parent-reported cognitive symptoms (group: $\beta = 3.11$, $p < .001$ and $\beta = -0.02$, $p < .001$ for intercept and slope, respectively; pre-injury symptoms: $\beta = 0.72$, $p < .001$ and $\beta = -0.002$, $p < .001$ for intercept and slope, respectively). Thus, participants in the concussion group, as well as those with greater pre-injury cognitive symptoms, reported greater symptoms at 10-days post-injury and experienced a faster rate of decline in symptoms over 6-months, compared to children in the OI group and those with fewer pre-injury cognitive symptoms. When primary predictors (i.e., CD-RISC, WASI-II FSIQ, TBV) were entered into the model separately, along with their corresponding group interactions, a significant effect of resilience was present for the intercept ($\beta = -0.14$, $p = .021$), indicating that greater resilience was associated with lower parent-reported cognitive symptoms at 10-days post-injury.

In the full model, with all covariates, predictors, and interactions entered, a significant effect of pre-injury cognitive symptoms was present for both the intercept and slope (β = 0.72, p < .001, β = -.002, p < .001 for slope and intercept, respectively), with greater pre-injury cognitive symptoms predictive of greater cognitive symptoms at 10-days post-injury, as well as a faster rate of decline in symptoms over 6-months. The effect of resilience on the intercept remained significant (β = -0.13, p =.037) in the full model. Neither IQ nor TBV were predictive of symptoms at 10-days or change in symptoms over time, even when they were each examined independent of the other primary predictors.

Parent HBI Somatic Domain

When group and covariates (i.e., age, sex, pre-injury somatic symptoms) were examined together, without the primary predictor variables, the concussion group reported worse somatic symptoms at 10-days post-injury and experienced a faster rate of decline in symptoms over 6-months, as compared to participants in the OI group (β = 4.36; p < .001, β = -0.03, p < .001 for intercept and slope, respectively). Greater pre-injury somatic symptoms predicted worse somatic symptoms at 10-days post-injury, as well as a faster rate of decline in somatic symptoms (β = 0.55, p < .001, β = -.001, p < .001 for intercept and slope, respectively). Older age at injury predicted worse parent-reported somatic symptoms at 10-days post-injury (β = 0.21, p = .003).

In the full model, with all covariates, predictors, and interactions entered, significant effects of age (β = 0.21, p = .005) and pre-injury somatic symptoms (β = 0.56, p < .001) were present at 10-days post-injury, with older age and worse pre-injury symptoms predictive of worse symptoms at 10-days post-injury. Worse pre-injury somatic symptoms were also predictive of a faster rate of decline in symptoms (β = -.001, p < .001). Resilience, IQ, and TBV were not predictive of parent-reported somatic symptoms at 10 days post-injury or change in symptoms over time, even when they were each examined independent of the others.

Child HBI Cognitive Domain

When group and covariates were examined together, without including primary predictor variables, a significant effect of group was present for the intercept and slope for child-reported cognitive symptoms ($\beta = 5.94$, $p < .001$; $\beta = -0.4$, $p < .001$ for intercept and slope, respectively), indicating that participants with concussion reported worse symptoms at 10-days post-injury and experienced a faster rate of decline in symptoms over 6-months, as compared to participants with OI. Females and older participants also reported worse cognitive symptoms at 10-days post-injury ($\beta = -2.28$, $p < .001$, $\beta = 0.44$, $p < .001$, respectively), and older participants also reported a faster rate of decline in symptoms ($\beta = -0.002$, $p = .028$). Retrospective ratings of worse pre-injury cognitive symptoms were a significant predictor of worse cognitive symptoms at 10-days post-injury ($\beta = 0.29$, $p < .001$).

In the full model, with all covariates, predictors, and interactions entered, significant effects of sex ($\beta = -2.34$, $p < .001$), age ($\beta = 0.53$, $p < .001$), pre-injury cognitive symptoms ($\beta = 0.23$, $p < .001$), and resilience ($\beta = -0.26$, $p < .001$), were found at 10-days post-injury, with female sex, older age at injury, worse pre-injury somatic symptoms, and lower resilience predictive of worse symptoms at 10-days post-injury. No variables were predictive of rate of decline in symptoms over time. Neither IQ nor TBV were predictive of symptoms at 10-days or change in symptoms over time, even when they were each examined independent of the other primary predictors.

Child HBI Somatic Domain

When group and covariates were examined together, without including primary predictor variables, children in the concussion group reported worse somatic symptoms at 10-days post-injury and experienced a faster rate of decline in symptoms over 6-months, as compared to those in the OI group ($\beta = 5.67$, $p < .001$; $\beta = -0.3$, $p < .001$ for intercept and slope, respectively). Female sex and worse pre-injury somatic symptoms predicted worse somatic symptoms at 10-days post-injury ($\beta = -1.55$, $p < .001$; $\beta = 0.40$, $p < .001$, respectively).

In the full model, with all covariates, predictors, and interactions entered, significant effects of sex ($\beta = -1.77$, $p < .001$), pre-injury somatic symptoms ($\beta = 0.39$, $p < .001$), and resilience ($\beta = -0.11$, $p = .023$) were present at 10-days post-injury, with female sex, worse pre-injury symptoms, and lower resilience predictive of worse symptoms at 10 days. No variables were predictive of change in symptoms over time. Neither IQ nor TBV were predictive of symptoms at 10 days or change in symptoms over time, even when they were each examined independent of other primary predictors.

Analyses of Effect of Site

Given the harmonization of the TBV data using COMBAT, which served to control for scanner differences, site was not included as a covariate in the primary models, as participants were not expected to differ on predictor or outcome variables as a function of hospital sites located in different Canadian cities. This assumption generally held true, with the exception of a potential confound among site location and parental education, as preliminary analyses indicated that a significantly greater number of participants with highly educated parents were recruited at the Vancouver site. Nevertheless, to determine whether any findings were confounded with site, four dummy variables were created to examine the effect of site (using Calgary as the reference) and were entered into the full HLM models. Hypothesis tests were conducted for each of the site dummy variables, as well as testing the overall effect of site across the four dummy variables. Of the 32 specific contrasts (4 for the slope and intercept for 4 outcomes), a significant effect of site was present only for the slope for child-reported cognitive symptoms, (χ^2 = 10.30, p = .035), with participants from the Vancouver site demonstrating a faster rate of decline in cognitive symptoms as compared to the Calgary site (β = -0.02, p = .005). Moreover, none of the overall multivariable tests of site was significant. Across all outcomes, the only change in results from those previously reported was that the effect of resilience on the intercept for the parent-report HBI cognitive domain was only marginally significant (β = -0.12, *p* = .052; previously significant in the full model without site included, β = -0.13, *p* =.037).

Correlational Analyses

Table 9 details the results of total sample and within-group correlations among resilience (i.e., CD-RISC), IQ (i.e., WASI-II FSIQ), and TBV. Controlling for age and sex, significant correlations were present between resilience and IQ in the total sample and OI group, though not in the concussion group. Additionally, a significant correlation was present between IQ and TBV in the total sample and concussion group, though not in the OI group. Group differences in correlations were significant for the relationship between IQ and TBV (Fisher's *z* = 2.67, *p* = .004), with a higher correlation in the concussion group than in the OI group. Notably, all correlations were small in magnitude.

Table 9
Correlations among predictor variables

	Overall Sample		Concussion		OI		Fisher's z; *p*	
	WASI FSIQ	**CD-RISC**	**WASI FSIQ**	**CD-RISC**	**WASI FSIQ**	**CD-RISC**	**WASI FSIQ**	**CD-RISC**
CD-RISC	.14*	-	.09	-	.21*	-	z = -1.25, *p* = .106	-
TBV	.11*	.01	.19**	-.01	-.07	.01	*z* = 2.67*, *p* = .004	*z* = -0.2, *p* = .842

Note: Controlling for age and sex
* Significant ($p < .05$)
** Significant ($p < .001$)

Discussion

The current study aimed to examine the roles of psychological resilience, cognitive reserve, and brain reserve in predicting trajectories of post-concussive symptoms in children who sustained a concussion, compared to children who sustained an OI. To date, this study is the first of which we are aware to examine all three factors in relation to outcome of pediatric concussion in a single model, and is the first to examine the role of brain reserve in pediatric concussion. Several hypotheses were tested, including analyses of the prediction of trajectories of PCS over time by resilience and reserve, analyses of moderating effects of resilience and reserve factors on group differences in trajectories of PCS, and exploration of the correlations among all three resilience and reserve factors. Psychological resilience, cognitive reserve, and brain reserve were treated as independent predictors of outcome, as well as moderators of group differences. Study hypotheses predicted (1) negative associations of psychological resilience, cognitive reserve, and brain reserve with PCS and trajectories of PCS, (2) moderation of group differences in PCS and trajectories of PCS by all three resilience and reserve variables, indicating stronger relationships between resilience/reserve and PCS among the concussion group, as compared to OI (or, alternatively, larger effects of concussion at lower levels of resilience and reserve), and (3) positive correlations among all three resilience and reserve variables. Analyses provided partial support for these hypotheses.

Full-model analyses did not support the roles of psychological resilience, cognitive reserve, or brain reserve as significant predictors or moderators of change in PCS over the first 6-months post injury. However, psychological resilience was found to be a significant predictor of parent- and child-reported cognitive symptoms, as well as child-reported somatic symptoms, at each time point. Group was not a predictor of symptoms or change in symptoms overtime in the full model, which may be related to the dilution of effects due to the number of predictors in the model. However, when group was isolated in the model with only covariates included, as well as in a partial model with only non-significant interactions removed, group significantly predicted both parent- and child-reported cognitive and somatic symptoms at the intercept, as well as a change in symptoms over time.

Irrespective of group membership, in the full model (i.e., inclusion of all predictors, interactions, and covariates), retrospectively rated pre-injury cognitive and somatic symptoms were significant predictors of parent- and child-reported somatic PCS, as well as parent-reported cognitive PCS, with worse pre-injury symptoms predictive of worse post-injury symptoms. Moreover, pre-injury symptoms significantly predicted change in parent-reported cognitive and somatic PCS over 6 months, indicating that higher pre-injury symptoms were associated with a faster rate of decline. Additionally, older age at injury was predictive of higher parent-rated somatic and child-rated cognitive PCS. Female sex also predicted worse child-reported cognitive and somatic PCS.

Taken together, analyses indicate that group, age, sex, pre-injury symptoms, and resilience are important predictors of PCS, though group and pre-injury symptoms appear more predictive of change in symptoms over time. Several potential explanations for the lack of significant findings related to the prediction of PCS by cognitive reserve and brain reserve can be offered.

First, although several studies have supported the relationship between cognitive reserve and PCS in TBI (e.g., Donders & Kim, 2019; Fay et al., 2010), few have examined these relationships specifically within concussion, which represents the mildest form of TBI. Thus, the fact that analyses within the current study contradict previous findings may be a function of injury severity. Previous research has provided limited support for lasting effects of concussion on formal tests of cognitive ability (e.g., Manley et al., 2017). Thus, children with concussion may display few decrements in neurological functioning to be moderated by cognitive reserve. Conceptualization of cognitive reserve as a neurological resilience factor (i.e., a mechanism that enables better compensation or efficiency of neural resources in the context of injury), is supported by previous studies that indeed show a relationship among cognitive reserve and cognitive functioning post moderate-to-severe TBI (e.g., Donders & Stout, 2019; Donders & Kim, 2019; Fraser et al., 2019). However, milder injuries, such as those associated with concussion, may lead to only minor nuanced changes in functioning with little neurological disturbance to be moderated, and thus not impacted by cognitive reserve (i.e., little brain damage to compensate for). This explanation is somewhat contradicted by Fay et al. (2010), who found cognitive reserve to be related to fewer PCS among children with concussion (both complicated and uncomplicated mild TBI). However, the majority of significant findings related to cognitive reserve in the Fay et al. (2010) study were with respect to the complicated mild TBI group, with only one significant moderation effect involving the uncomplicated mild TBI group, which was significant only early in recovery (i.e., 1-month post-injury), though not later in recovery.

Several published studies supporting the protective role of cognitive reserve among children with TBI have utilized more indirect measures of cognitive reserve in children, such as parent education (e.g., Donders & Kim, 2019), which may tap more into SES than true cognitive reserve. While SES is shown to have high overlap with cognitive reserve (Jones et al., 2012), SES encompasses the broader environment, and is therefore likely to account for higher variability in outcome of concussion (Taylor et al., 2010) than a more direct measure of cognitive reserve, such as IQ. Nonetheless, the lack of a significant relationship of IQ with PCS in the current study supports other previous null findings regarding the relationships among cognitive reserve and outcome of TBI (e.g., Mahdavi, Hasper, & Donders, 2019; Fuentes, McKay, & Hay, 2010), although most previous studies have focused on objective tests of cognitive functioning as outcomes rather than PCS.

Studies of the role of brain reserve in the prediction of outcomes of TBI of all severities, including concussion, are scarce. Only one identified study has examined this relationship, and found brain reserve to be predictive of change in pre/post-injury IQ among individuals with moderate to severe TBI (Kelser et al., 2003). Based on findings of the current study, greater TBV does not appear to be related to individual differences in PCS or to act as a buffer against PCS or PCS trajectories in children with concussion or orthopaedic injury. Again, given the mild nature of the injury, brain volume may be less relevant in the context of relatively minor physical changes in the brain.

Our findings suggest that PCS, while impacted by the effects of concussion, are also related to the perception of everyday fluctuations in commonly experienced physical and cognitive symptoms (e.g., headaches, difficulties concentrating), which may be impacted by resilience, rather than injury factors alone. This argument is supported by the finding that more pre-injury symptoms, unrelated to injury, were predictive of more post-injury symptoms. Furthermore, psychological resilience was found to be significantly negatively correlated with pre-injury somatic and cognitive symptoms (r = -.27, p < .001 and r = -.15, p = .001, respectively), indicating that individuals with lower resilience are more likely to report cognitive and somatic symptoms even when they are unrelated to the experience of an injury.

Psychological factors appear to be a more important predictor of PCS in comparison to neurological reserve factors, although resilience did not predict change in symptoms over time. The significant findings with respect to the effect of group on change in symptoms suggests that concussion results in higher symptoms in the post-acute phase, which subsequently resolve faster, though resilience likely continues to explain variation in symptoms later in time. The current findings regarding the role of psychological resilience in the prediction of PCS in pediatric concussion is consistent with previous research (Laliberté Durish, Brooks, & Yeates, 2018; 2019). Interestingly, psychological resilience differed among the injury groups, with the concussion group reporting lower resilience than the OI group during the post-acute assessment. Given the effect of group on symptom endorsement, it is possible that the experience of worse symptoms resulting from a concussion may impact one's perception of resilience. Given that research supports a correlation among resilience and psychological symptoms (e.g., Laliberté Durish, Yeates, & Brooks, 2018b; Laliberté Durish, Brooks, & Yeates 2018a), the current findings indicate that injury may result in increased psychological symptoms, thereby affecting perception of resilience. Furthermore, psychological symptoms are supported as a mechanism by which psychological resilience affects PCS (Laliberté Durish, Brooks, & Yeates, 2019), such that lower resilience is related to greater anxiety and depressive symptoms, which lead to worse PCS.

Findings with respect to the correlations among psychological resilience, cognitive reserve, and brain reserve, indicated a significant, although small, overlap in these measures. While the magnitude of correlations were small, the results indicate that resilience and reserve factors share at least some similar features, in that higher resilience is associated with higher IQ, and that higher IQ is associated with larger TBV. However, the significance of these correlations is in part a function of the large sample size. Previous research has not consistently supported a relationship among resilience, IQ, or total intracranial brain volume in TBI (e.g., Hanks et al., 2016; Rapport, Wong, & Hanks, 2019; Kelser et al., 2003). The finding that IQ and TBV were more highly correlated among the concussion group, compared to the OI group, while significant, may be less relevant in the context of relatively small magnitudes of the correlations.

Limitations

Several limitations exist with respect to the current study, and should be used to guide future research efforts on the topic of resilience and reserve in pediatric concussion. First, previous research on cognitive reserve in TBI indicates that it may be best captured in a multifactorial manner (Levi et al., 2013). Thus, understanding of the role of cognitive reserve in predicting outcomes of PCS in children was limited in the current study by the focus on one variable, IQ, as a measure of cognitive reserve. As such, a child's environment (identified as an important contributor to cognitive reserve in children; Dennis et al., 2007) may not be adequately captured by this unitary measure. Secondly, brain volume has been shown to fluctuate in response to concussion (Jarrett et al., 2016; Churchill et al., 2016). This has implications for the use of TBV measured at a single timepoint as a proxy of brain reserve, which is thought to be static in nature. Relatedly, other proxies of brain reserve, such as white matter integrity, may be more relevant to studying reserve in the context of concussion, particularly given that larger brain volume is not necessarily associated with better functioning in children (e.g., Hardan et al., 2009). Third, the sample was focused on children who presented to the emergency department following injury, therefore limiting the generalizability of the findings to children who do not present to emergency. Fourth, preliminary analyses indicated some selective attrition among participants with complete and incomplete datasets for the purposes of HLM analyses (i.e., full data on predictor variables, collected at the post-acute and 3-month follow-ups). Participants with incomplete data had slightly worse symptoms at the 3- and 6-month follow-ups. Therefore, the sample utilized in the analyses may have represented a slightly healthier population. Moreover, preliminary analyses indicated Indigenous participants were far more likely than any other ethnic group to be lost to follow-up, pointing to further biases in the sample as well as highlighting challenges associated with representing Indigenous peoples in research (Hyett et al., 2018). Fifth, findings of trauma-related abnormalities on MRI/CT were not controlled. While preliminary analyses suggested very few participants demonstrated abnormalities on CT during their initial ED visit (e.g., one skull fracture), suggesting the sample primarily consisted of children with concussion rather than complicated mild TBI, incidental findings were not assessed on the MRI completed at the post-acute visit, therefore potentially biasing the sample. Lastly, PCS were measured at only 3 time points, therefore limiting more sophisticated modelling techniques such as quadratic trajectories or capturing of more subtle changes in symptoms earlier in recovery.

Future Directions

Results of the current study point to the role of psychological resilience in predicting fewer post-concussive symptoms. However, positive outcomes of illness or injury do not necessarily refer to the absence of symptoms. Future research efforts should aim to examine positive outcomes such as quality of life. Further, mechanisms by which psychological resilience leads to improved outcomes should be explored. For example, positive affect may act as an important mechanism by which resilience promotes optimal cognitive functioning in children with concussion, given its impact on cognitive functioning in general (e.g., Ashby & Isen, 1999). Additionally, given that the relationship of reserve and resilience to outcomes of concussion could fluctuate with age, future studies should explore changes in resilience and reserve over time, and how such changes might influence the outcome of concussion, as well as inform interventions. Relatedly, given the modifiability of resilience through intervention (Donnelly et al., 2019), research should be directed towards exploring interventions aimed at increasing resilience to improve outcomes for children with concussion. Lastly, given that measurement of resilience depended on self-report, future studies might incorporate multi-modal measures to better capture the broader construct of resilience (i.e., family and social factors), as they relate to children. Relatedly, future studies should also more comprehensively evaluate cognitive reserve in a multi-factorial manner to better understand its implications on outcome of concussion and potential modifiability.

Conclusions

In conclusion, results of the present study support the role of psychological resilience as a predictor of fewer PCS among children with concussion or OI. However, cognitive and brain reserve do not appear to impact PCS after concussion and the impact of resilience on PCS did not differ among injury groups. These findings provide further support for PCS as stemming, in part, from psychological phenomena related to how well an individual tolerates adversity. Thus, these results highlight the importance of exploring psychological correlates of concussion, rather than merely focusing on injury-related changes. Additionally, the present study contributes to the growing body of literature on predicting wellness after concussion, and serves to identify protective factors that potentially can be harnessed through intervention to improve outcomes for children with concussion.

Concluding Remarks

The two studies described herein sought to better understand the roles of resilience and reserve in pediatric concussion, as predictors of improved outcome. Taken together, the majority of existing published research on the topic of resilience and reserve in TBI indicate resilience and reserve act as important protective factors in buffering the effects of negative cognitive, social, psychological, and physical outcomes of TBI, with more research generated in the areas of resilience and cognitive reserve, particularly in the context of adult TBI. To our knowledge, no research has been published that examines the role of brain reserve in the context of pediatric TBI, or concussion in any age group. The second study addressed this significant research gap by examining the role of brain reserve in pediatric concussion. Results did not support a relationship of brain volume, measured as a proxy of brain reserve, to PCS. An explanation regarding the null findings with respect to the relationship among brain reserve and PCS is related to the possibility that limited physical damage sustained by the brain leaves little to be buffered by brain volume. A similar argument was presented with respect to null findings regarding the relationship among cognitive reserve and PCS.

The main finding of the second study was the relationship of resilience to PCS. Though the data did not demonstrate a relationship of resilience to change in PCS over time, resilience was nonetheless a significant predictor of PCS at all time points. Group appeared to be a stronger predictor in change in PCS over time, in that participants with concussion experienced a faster rate of decline in symptoms, as compared to participants with OI. Overall, findings indicate that injury factors appear to predict PCS in the short term, where as non-injury factors are more likely to account for persistent symptoms. Such findings are consistent with existing research suggesting the same (e.g., McNally et al., 2013).

Study 1 identified a number of studies examining the role of cognitive reserve in TBI; however, relatively few studies were identified that examined cognitive reserve specifically in the context of concussion/mild TBI (e.g., Stenberg et al., 2020; Mahdavi, Hasper, & Donders, 2019; Steward et al., 2018; Wright et al., 2016; Oldenburg et al., 2016; Fay et al., 2010) Moreover, only two studies specifically examined cognitive reserve in children with concussion/mild TBI (Mahdavi, Hasper, & Donders, 2019; Fay et al., 2010), and found conflicting results, albeit using different proxies (i.e., post-injury cognitive functioning versus parental education). The second study aimed to address this void in the literature by examining a more direct proxy of cognitive reserve (i.e., estimated IQ) in children with a history of concussion and did not support a significant relationship among cognitive reserve and PCS. Null findings indicate that minor injuries with relatively little direct impact on cognitive functioning may not be impacted by cognitive reserve factors, which normally serve to mitigate neuronal impairment in the context of injury.

Study 2 also aimed to examine the relationships among resilience and reserve, which was identified as a significant gap in the literature explored in Study 1. Findings indicated minimal, though significant, overlap among the constructs of resilience and cognitive reserve, as well as cognitive reserve and brain reserve. Results indicated that children with an injury history (i.e., concussion or OI) who have higher IQ also demonstrate greater resiliency and have larger brain volumes. Brain volume and resilience were not found to be significantly correlated. Future research should be aimed at identifying mechanisms of these relationships to better elucidate a more cohesive model of resilience and reserve in a pediatric population.

A limitation that the second study did not address was the argument presented in the scoping review that promoted the use of a multifactorial measure of cognitive reserve, rather than merely relying on a single, unitary proxy. The second study utilized estimated full scale IQ as the only proxy of reserve. Ideally, cognitive reserve appears to be best captured by examining multiple factors, such as education, occupational functioning, pre-morid IQ, SES and social/leisure functioning (Levi et al., 2013; Menardi et al., 2020). However, challenges inherent to measuring cognitive reserve in children precluded us from utilizing a multifactorial proxy (i.e., education and occupational functioning are less applicable to children). Future studies should better describe cognitive reserve factors that may be more applicable within a pediatric population, such as social functioning and activity involvement (e.g., sports/leisure, clubs, music/arts), that may comprise a composite cognitive reserve score when combined with measures of IQ, parental education, and parental occupation. A multifactorial questionnaire used in the Menardi et al. (2020) study (i.e., Cognitive Reserve Index questionnaire) that captured education, working activity, and leisure activity may represent an appropriate framework for measuring cognitive reserve if tailored to relevant cognitive reserve factors in children.

Overall, this body of research represents an important contribution to the literature aimed at better understanding predictors of improved outcomes following concussion. Existing literature was summarized in Study 1, and Study 2 contributed findings indicating the significant role of psychological resilience as a buffer against cognitive and somatic PCS. Measuring resilience post-injury can improve the identification of children who are at risk for poor outcomes of concussion. More importantly, results of the research presented herein indicate potential avenues for interventions aimed at improving outcomes for children with concussion. Specifically, interventions that harness and improve resilience and reserve factors may serve to improve outcomes for children who sustain concussion.

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