# Chapter 5
# Executive Dysfunction After Traumatic Brain Injury

**Mauricio A. Garcia-Barrera, F. Taylor Agate, Ryan E. Wong, Colette M. Smart and Justin E. Karr**

## 5.1 Introduction

Sam is a 19-year-old female varsity soccer player, at the center forward position, who sustained a sports-related concussion during her last game. This was a high-stakes game, as her team was competing for a championship. Earlier in the game, Sam experienced a head-to-elbow collision against another player; she collapsed to the ground without losing consciousness or incurring an open head wound, recovered within 30 s, and continued playing. Later, she recalled having felt dizzy and experiencing some acute-onset nausea. Her head was pounding in anticipation of a headache. She ignored these symptoms as the game continued. During the second half, within the same game, Sam found herself in position to receive a long ball pass from their team's goalkeeper, a pass they have rehearsed several times during practice. With a quick head rotation, her heading of the ball was astute, precise, and she achieved a goal. Her team jumped in celebration, while she collapsed to the ground and could not stand up. She was carried off of the field on a stretcher, and the sports physician on site ordered an ambulance for admission to the local hospital's emergency department (ED). Another player reported she might have lost consciousness for a few seconds while lying in the grass. Video examination confirmed that she remained in the grass immobile for about 6 s before being awakened by other players. Although Sam recalled most of the game, she did not recall details of the incident, or having scored a goal. Her Glasgow Coma Scale (GCS) score was 13 out of 15. Sam was diagnosed with mild Traumatic Brain Injury (mTBI) and was hospitalized for 3 days for preventive monitoring as her computerized tomography

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M. A. Garcia-Barrera (✉) · F. T. Agate · R. E. Wong · C. M. Smart
Department of Psychology, University of Victoria, Victoria, BC, Canada
e-mail: mgarcia@uvic.ca

J. E. Karr
Department of Physical Medicine and Rehabilitation, Harvard Medical School, Spaulding Rehabilitation Hospital, Home Base, A Red Sox Foundation and Massachusetts General Hospital Program, Boston, MA, USA

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(CT) scan revealed a small intracranial hematoma in her frontal lobes. Surgery was not required, and anti-inflammatory medication was administered to diminish risk of brain swelling.

Sam was evaluated by a clinical neuropsychologist 2 months later. The clinical interview revealed a past history of two unreported concussions, both sports-related and without loss of consciousness. She had clinically recovered from the recent mTBI, presenting no neurological signs during examination, but reported difficulty with problem-solving and making decisions, as she felt quickly overwhelmed and emotionally dysregulated; she also reported feeling defensive when others pointed out she was not herself. With guidance from coaches and her family doctor, she had progressively returned to soccer practice, and was regaining fitness, but reported to have withdrawn from social interactions with team members outside of practice. She was feeling isolated but unmotivated to initiate engagement. Her fear about experiencing another concussion had arisen and was a major concern for her, producing a heightened anxiety. On testing, Sam's overall performance was within normal limits for most areas assessed, and her performance level was consistent with estimated levels of premorbid functioning based on word reading and pre-injury school performance. There was no baseline testing available. Sam is majoring in business and was considered a B+ student. However, there were reports of diminished performance in school post-concussion, mostly due to difficulty concentrating during midterm exams despite extended time allowance and having missed a few deadlines due to disorganization with her calendar. Sam's self-ratings on the Behavior Rating Inventory of Executive Function (BRIEF) demonstrated self-awareness of her everyday difficulties, which were also confirmed by parents' report. Given the risk of more concussive events, Sam was recommended psycho-education, to gain knowledge about sport-related concussion symptoms and expected recovery trajectory, informing any future return-to-play decisions. She was also recommended individual psychotherapy to work on her social withdrawal and anxiety, in addition to cognitive rehabilitation of executive functions with a problem-solving focus to work on her difficulties with planning, problem-solving, emotional regulation, and disorganization. Given her CT scan, she was recommended to continue soccer practice but to withdraw from playing competitive soccer for 12 months. Follow-up CT scan and neuropsychological assessment 13 months later revealed a full recovery, and Sam reported that she discussed with coaches a gradual return to competitive play, but she stopped heading practice and changed field positions; now she is playing on a right-midfield position in which she has been able to reduce her ball heading during games down to zero.

## 5.2 Traumatic Brain Injury

### *5.2.1 Definition*

Sam suffered an mTBI. Although the term "Traumatic Brain Injury" (TBI) seems self-explanatory, there is no one sole definition available in the literature. Researchers have moved from the vague "head injury" terminology, to terms that emphasize damage to the brain structure and function. Looking for parsimony, a consensus position statement from The Demographics and Clinical Assessment Working Group of the International and Interagency Initiative toward Common Data Elements for Research on Traumatic Brain Injury and Psychological Health, refers to TBI as "an alteration in brain function, or other evidence of brain pathology, caused by an external force" (Menon Schwab, Wright, & Maas, 2010; p. 1638). With this definition, it is further proposed that an *alteration in brain function* may present as (1) loss of or decreased consciousness (LOC), (2) loss of memory of the event and the periods before or after it, (3) the presence of neurological deficits such as muscle weakness, loss of balance, change in vision, or (4) alteration in mental state, such as confusion, disorientation, etc. Only one of these clinical signs is required. Also, *evidence of damage* to the brain may include neuroradiological, visual, or other laboratory tests, and the *external force* may include the head being struck or penetrated by an object, sharp acceleration and deceleration movement, forces generated by an explosion or blast, etc. (Menon et al., 2010).

TBI severity is classified on a continuum, ranging from mild to moderate to severe. About 80% of traumatic brain injuries are mild (Bruns & Hauser, 2003). Most of the debate has arisen from the diagnosis of mild TBI, and in establishing proper guidelines to differentiate injury severities. The most frequently used index of TBI severity is the Glasgow Coma Scale (GCS, Teasdale & Jennett, 1974). This scale produces a score from 3 to 15, including examination of responsiveness in eye opening, and level of verbal and motor response. The higher the score, the better the response. It has been proposed that a score between 3 and 5 corresponds to a very severe brain injury, a score between 6 and 8 is associated with a severe brain injury, 9–12 corresponds to moderate, and a score between 13 and 15 is associated with mild brain injury. Some authors proposed that the presence of positive CT scan findings (as in Sam's case) would be considered as a complicated mTBI (Roebuck-Spencer & Sherer, 2008). The now-classic scale is free and can be downloaded from this Web site: https://www.glasgowcomascale.org/.

The scores obtained with the GCS offer robust indicators of prognosis, but they can be affected by several factors, including patient's intoxication at admission, facial injuries, and aphasia that can compromise verbal response, visual or auditory processing, and early management such as intubation and medications (e.g., sedatives and other anesthetic drugs). The Glasgow Outcome Scale (GOS, Jennett & Bond, 1975) has been used to measure recovery outcome after TBI. The best outcome is "good recovery" for a full functional recovery with some residual emotional or cognitive lingering deficits; "moderate disability" for some recovery of function, reflective of some independent living but presenting with inability to return to work or function socially; “severe disability” when the patient is conscious but requires full support to meet their physical and cognitive needs; and “vegetative state” when the patient is unable to communicate and follow commands, and there is no other discernable cognitive functioning (Lezak, Howieson, Bigler, & Tranel, 2012; Roebuck-Spencer & Sherer, 2008). Other diagnostic and predictive factors that have been proposed include duration of coma ($\leq$20 min = mild, $\leq$6 h = moderate, and >6 h = severe injury; Lezak, Howieson, Loring, Hannay, & Fischer, 2004), and duration of post-traumatic amnesia (PTA; <5 min = very mild, 5–60 min = mild, 1–24 h = moderate, 1–7 seven days = severe, 1–4 weeks = very severe, and >4 weeks = extremely severe; Lezak et al., 2012; p. 185). Although length of PTA is a better predictor of global outcomes than coma duration and than the GOS (Lezak et al., 2012), it is recognized that these variables have poor predictive power when in isolation (Roebuck-Spencer & Sherer, 2008).

In Sam’s case, she meets criteria for a diagnosis of complicated mTBI, and she experienced a short LOC (estimated at 6 s) and had a PTA of less than 5 min, and her GOS would classify her in the “good recovery” category. Even though we would expect positive neuropsychological findings (e.g., poor performance in a few areas), her overall performance was “within normal limits,” but in the absence of prior testing, some acute cognitive capacity loss could have been masked. Her recovery was remarkable, and somewhat unpredicted by the presence of PTA and LOC. Researchers have discussed potential confounders that muddle the precision of the diagnosis of mTBI (Menon et al., 2010; Ruff et al., 2009). For instance, accounts of PTA can be confounded by the LOC; accounting for the LOC period can be problematic, as a delayed LOC could be a consequence of other secondary issues, not necessarily the original TBI (e.g., intracranial pressure due to extradural hematoma, or seizure activity); some of the information obtained by the clinician may be the outcome of self-experience, whereas some may be the outcome of information relayed to the patients by others. For instance, in Sam’s case, she could not report LOC with confidence due the PTA. Another issue is that the PTA may be associated with stress (as in psychogenic amnesia observed in cases of posttraumatic stress disorder -PTSD), not necessarily the brain injury. Similarly, the LOC and PTA could be the outcome of substance use before the accident, or drugs administered to the patient while in transport to the ED. Finally, some of the symptoms that are relevant to diagnosis are less specific to TBI (e.g., fatigue, headache, sleep disorders), and could be best accounted for by stress, depression, PTSD, or anxiety).

The definition of mTBI is an area of continuing debate. A review of mTBI by the World Health Organization (WHO) identified 38 definitions of mTBI with varying degrees of overlap. Based on these findings, the WHO proposed the following operational definition:

> mTBI is an acute brain injury resulting from mechanical energy to the head from external physical forces. Operational criteria for clinical identification include: (1) One or more of the following: confusion or disorientation, loss of consciousness for 30 min or less, post-traumatic amnesia for less than 24 h, and/or other transient neurological abnormalities such as focal signs, seizure, and intracranial lesion not requiring surgery; (2) Glasgow Coma Scale

> score of 13–15 after 30 min post-injury or later upon presentation for health care; (3) these manifestations of mTBI must not be due to drugs, alcohol, medications, caused by other injuries or treatment for other injuries (e.g., systemic injuries, facial injuries, or intubation), caused by other problems (e.g., psychological trauma, language barrier, or coexisting medical conditions), or caused by penetrating craniocerebral injury. (Kristman et al., 2014, p. S266)

### *5.2.2 Neuroimaging Techniques as Useful Instruments in Examining the Outcomes of MTBI*

Given the difficulty in properly identifying and diagnosing instances of mTBI, and the reliance on self-report, alternative methodologies have been developed. Early studies on concussion noted that neuropsychological testing had limited utility at detecting mTBI (Binder, Rohling, & Larrabee, 1997); however, meta-analytic evidence suggests that clinical neuropsychological assessment can reliably detect mTBI symptoms (or lack thereof) in the acute phase of the injury, but appears to fail to detect and/or predict long-term cognitive deficits in mTBI patients (Martin, 2003). Neuropsychological assessment has in fact become a common method for evaluating the sequelae of mTBI, particularly in cases classified as complicated (such as Sam's). Neuropsychological assessment was included in the recent recommendations for the assessment of long-term effects of sports-related concussions (McCrory et al., 2017). Past researchers have applied several tests to evaluate post-mTBI cognitive outcomes among working adults (Sherer et al., 2002); however, no gold-standard instrument exists for the neuropsychological assessment of workers following occupational mTBI. Although past studies have historically used validated paper-and-pencil assessment tests to evaluate the cognitive outcomes of mTBI, recent advances in computerized neuropsychological assessment have emphasized the added sensitivity of response time (RT) data at detecting impairment following mTBI (Collie, McCrory, & Makdissi, 2006; Iverson, Brooks, Lovell, & Collins, 2006; Sosnoff, Broglio, Hillman, & Ferrara, 2007). Further, specific cognitive abilities appear vulnerable to the effects of mTBI based on past meta-analytic findings, including memory, processing speed, and executive functions (Belanger, Curtiss, Demery, Lebowitz, & Vanderploeg, 2005; Belanger, Spiegel, & Vanderploeg, 2010; Frencham, Fox, & Maybery, 2005; Zakzanis, Leach, & Kaplan, 1999).

Based on these considerations, the best instrument for a cognitive evaluation of mTBI would assess these cognitive domains through reliable and valid computerized tests with accurate RT measurement. Recently, the National Institute of Health (NIH) has developed a Cognition Battery known as the **NIH-Toolbox**, which provides a computerized toolkit of neuropsychological tests evaluating cognitive domains such as crystallized knowledge, memory, processing speed, and executive functions. Notably, although crystallized knowledge should not decrease as a result of concussion, these tasks measure a level of premorbid ability and provide guidance on the level of a participant's functioning prior to head injury. As a validated tool for the cognitive assessment of adults (Weintraub et al., 2014), the NIH-Toolbox has established psychometric qualities, including convergent validity with gold standard measures currently used for neuropsychological assessment (Mungas et al., 2014). The composite scores for the toolbox (i.e., crystallized, fluid and total cognition) present high test–retest reliability ($r = 0.92$, 0.86, and 0.90, respectively) and only small to medium practice effects (Heaton et al., 2014), making the variables largely appropriate for a longitudinal design so long as the analytical methods take the impact of repeated measurement into consideration (Cysique et al., 2011). The NIH-Toolbox includes tests for the assessment of *Executive functions such as:* (1) Flanker Inhibitory Control and Attention: The participant views an arrow central to the screen and other arrows on either side in the same or opposite direction. The participant must identify the direction of the central arrow and ignore the directions of the other arrows; and (2) Dimensional Change Card Sort: The participant observes two pictures that vary based on shape and color. The participant must match these shapes to a target shape based on shape and color, but the correct dimension by which to sort will change during a switch task, which requires the individual to shift back and forth with changing task rules.

From a clinical perspective, neuroimaging techniques are widely used to diagnose moderate and severe brain injuries, although traditional techniques (e.g., CT, T1-weighted MRI) are not sensitive to the microstructural damage and small tears associated with mTBI, and it is only in some complicated cases, such as Sam's, when the CT scan may show positive findings. Although not yet used for diagnostic purposes, two of the most common neuroimaging techniques for detecting and studying mTBI in research settings are Electroencephalograms (EEG), and advanced magnetic resonance imaging (MRI, both structural approaches and functional—*f*MRI) (Eierud et al., 2014). These techniques have demonstrated that a main outcome of the brain injury sustained after a concussion is mostly circumscribed to axons and the bundles they form; structures that comprise white matter tissue in the brain (Shenton et al., 2012). Specifically, mTBI often involves twisting and shearing of axons. Such axonal injuries can cause changes in brain function, but are not typically visualized with traditional brain imaging techniques, such as CT or high-resolution T1-weighted MRI scans. An alternative method is diffusion tensor imaging (DTI), an MRI-based technique that can be used to measure the diffusion of water in the brain. Given that diffusion occurs parallel to axon bundles, rather than perpendicular, DTI is particularly useful in the study of white matter tissue. In fact, DTI imaging is emerging as a strong candidate for detecting long-term white matter structural brain anomalies associated with chronic cognitive deficits of mTBI, which traditional clinical neuropsychological assessments may fail to detect (Eierud et al., 2014; Shenton et al., 2012). Specifically, DTI results reveal decreased integrity in white matter regions (as evidenced by increased mean diffusivity and decreased fractional anisotropy) following mTBI (Cubon, Putukian, Boyer, & Dettwiler, 2011; Kinnunen et al. 2010; Messé et al., 2011). The mild injuries visualized with DTI can be diffuse, but are often seen in large white matter tracts, such as the corpus callosum and internal capsule (Sharp & Ham, 2011). Importantly, DTI results have been shown to positively correlate with cognitive impairment following mTBI (Kinnunen et al., 2010; Lipton et al., 2009), and to relate to post-concussion symptoms (Inglese et al., 2005). More recently, DTI has been used longitudinally, at 2 weeks and 2 months post-injury, to examine changes in white matter tracts after sports-related mTBI. The results showed changes in DTI-based metrics (e.g., radial diffusivity) over time, providing evidence that DTI is a sensitive measure of neurological recovery following concussive injury (Murugavel et al., 2014).

Along with structural injury come changes in brain function. Such changes can be reliably captured with techniques such as *f*MRI and EEG. Functional MRI is a technique that allows for the visualization of the brain in action. Essentially, structural MRI collects high-resolution images of the brain that can be combined with blood-oxygen level-dependent (BOLD) *f*MRI to track blood flow in the brain during a cognitive task or at rest. Since the conception of *f*MRI in the early 1990s (Ogawa et al., 1992), significant advances in research have broadened our understanding of how the brain functions under both healthy and diseased conditions (e.g., Dolan, 2008; Haller & Bartsch, 2009; Rosen, Buckner, & Dale, 1998). Using functional connectivity approaches from *f*MRI, researchers have identified a set of functional networks that appear to be associated with executive control, such as the cognitive control network (Cole, Pathak, & Schneider, 2010) and the fronto-parietal and cingulo-opercular networks (Fair, Dosenbach, Church, Cohen, & Brahmbhatt, 2007). However, relatively few studies have used *f*MRI to assess concussion. According to a review, approximately 20 studies have used *f*MRI to examine mTBI (McDonald, Saykin, & McAllister, 2012). In spite of this, functional imaging has been identified as a novel technological platform that has clinical potential for concussion evaluation (McCrory et al., 2017). To date, studies have revealed differences in brain activation in mTBI groups compared to healthy controls, even when behavioral performance is equivalent (McDonald et al., 2012). One of the few studies in concussions using resting-state *f*MRI revealed differences in functional connectivity between mTBI and controls (Mayer, Mannell, Ling, Gsparovic, & Yeo, 2011).

Mathematical models derived from graph theory have been recently used to analyze brain network organization (Bullmore & Sporns, 2009). Graph theory characterizes the brain as a set of networks. Each network is made up of distinct brain regions called nodes. The graph theory approach allows for the quantitative analysis of network properties such as organization and efficiency, and characterizes the network according to both global (whole brain) and local (specific brain regions) attributes. The healthy human brain generally functions as an efficient “small-world” network, characterized by connections between nodes that allow for both local specialization and global integration (Watts & Strogatz, 1998). In contrast, a “random” network is characterized by connections that promote global integration but not local specialization, and an “organized” network promotes local specialization but not global integration. Investigation with graph theory analysis of adult concussion/mTBI demonstrates a shift toward suboptimal network organization (Caeyenberghs et al., 2014; Nakamura, Hillary, & Biswal, 2009; Pandit et al., 2013). Resting-state EEG is a useful technique to capture differences in the global and/or local connectivity measures of network organization. These analytical approaches have been applied in adolescents who have experienced concussion (Virji-Babul et al., 2014).

### 5.2.3 How Prevalent Is TBI?

Sam's mTBI is one on millions of the yearly diagnosed TBIs in the world. There is variability in the accounts of prevalence and incidence of TBI both in the world and within nations, due to differences in the parameters used for the diagnosis of TBI in a given population (e.g., no LOC is required to diagnose a mTBI in cases such as sports-related concussion, but it is often used for other mTBI cases). Most published work report prevalence data from developed nations that have invested in epidemiological record keeping. Worldwide reports estimate that at least 10 million TBIs resulting in either hospitalization or death occur annually; as a result, an estimated 57 million people have been hospitalized due to having experienced a TBI (Langlois, Rutland-Brown, & Wald, 2006). A meta-analysis including 25,134 individuals from a selected pool of 15 papers (out of 1261 articles yielded by the search) examined the prevalence of TBI in adults in the USA, Australia, New Zealand, and Canada, finding a general prevalence rate of 12.1% when the diagnosis of TBI is specifically delimited by the presence of LOC (Frost, Farrer, Primosch, & Hedges, 2013). In the USA alone, there were close to 2.8 million TBI-related ED visits, hospitalizations, and deaths in 2013 (Taylor, Bell, Breiding, & Xu, 2017a). Over 5 million Americans that survived their TBI are dealing with the long-term outcomes (including lifelong disability) associated with injuries severe enough to have required hospitalization (Langlois et al., 2006). In Europe, TBI is listed as one of the top three causes of highest injury-related medical costs (Maas, Stocchetti, & Bullock, 2008). According to data from the Center for Disease Prevention and Control, the leading causes of TBI in adults (when known and when visits to the ER, hospitalizations and death rates are considered) are falls, motor vehicle traffic accidents, struck by or against events, and assaults, in that order (Frost et al., 2013; Langlois et al., 2006). Of those, traffic accidents are also the leading cause of TBI-related death (Faul, Xu, Wald, & Coronado, 2010), and the World Health Organization (WHO) projected that by 2020 it will be among the top causes of global burden of disease and injury (Maas et al., 2008).

There were a few risk factors detected by epidemiological research. Consistent with other epidemiological studies (e.g., Faul et al., 2010; Langlois et al., 2006), Frost and colleagues' meta-analysis found an odds ratio of 2.22 ($p \leq 0.0001$) for **gender** indicating that men are at twofold higher risk of suffering a TBI than women. This gender difference may be associated with a higher rate of men engaging in risky behaviors, contact sports and substance use (e.g., alcohol) (Frost et al., 2013). However, an area of growing concern is the increasing amount of woman experiencing intimate partner violence (IPV)-related TBIs, which are particularly unreported, unaccounted, and under-investigated mild TBIs. Valera, Campbell, Gill, and Iverson (2019) reported that "Approximately one-third of women globally have experienced physical or sexual IPV (Devries et al., 2013) and in a group of community and shelter women who had experienced IPV, it was shown that approximately 75% sustained at least one IPV-related TBI […]" (p. 2). In the USA alone, that number is estimated to be approximately 31,500,000 (Valera et al., 2019), a staggering and worrisome proportion, considering the aftermath effects of mTBI. Overall, violence is the cause of closed head injury in 7–10% of cases based on studies in the USA and China (Maas et al., 2008). In Canada, results from the Canadian Community Health Survey demonstrated a significant 10-year trend in increased self-reported traumatic brain injury among Canadians seeking care in EDs within the first 48 h post-injury, with 30,879 patients admitted in 2005, 45,452 in 2009, and 79,037 in 2014 (Rao, McFaull, Thompson, & Jayaraman, 2018).

**Age** emerged as another risk factor, with children 0–4, older adolescents 15–19, and older adults (≥65 years old) presenting as the groups at higher risk for TBI (Faul et al., 2010; Langlois et al., 2006). Adults over 75 years of age present the highest prevalence of hospitalization and death after TBI (Faul et al., 2010). In a report by Coronado et al. (2015), an estimated 329,290 children (age 19 or younger) were treated in US EDs in 2012 for sports and recreation-related injuries that included a diagnosis of concussion or TBI, showing a twofold increase from 2001 to 2012. Consistent with the literature identifying gender and age as risk factors for TBI, a systematic review we conducted synthesizing the data from 11 meta-analyses meeting inclusion criteria, identified that females and high school adolescents presented with the highest deficits on cognitive outcomes, including executive functioning, which was the most sensitive to the effects of multiple mTBI (Karr, Areshenkoff, & Garcia-Barrera, 2014b).

The following sections focus on a review of the effects of TBI on executive functioning across the lifespan, with an emphasis on four vulnerable groups: children and adolescents (**pediatric TBI**), and in adults (**occupational TBI**, **sports-related concussions**, and **military TBI**). Chapter 8 in this book includes discussion of executive dysfunctions observed in older adults.

## 5.3 Pediatric TBI and Executive Functioning

Pediatric brain injuries are a significant and growing concern, especially mTBI. Epidemiology studies in the USA reported that just from 2005 to 2009, children made over 5 million visits to either outpatient clinics (2 million) or the ED (3 million) seeking care for mTBI (Mannix, O'Brien, & Meehan III, 2013). According to the electronic database of the Canadian Hospitals Injury Reporting and Prevention Program, approximately 46,000 concussion s were reported in children and adolescents between the ages 5–19 years from 2016 to 2017 (Government of Canada, 2018). Overall, preventable injuries lead to nearly 3.5 million ED visits with a total economic cost of 26.8 billion dollars each year in Canada (Parachute Canada, 2015). Among those adolescents entering EDs with sports-related head injuries, the vast majority suffers from concussions with over 15,000 individuals visiting EDs in Alberta and Ontario in 2015 alone (Canadian Institute for Health Information, 2016). Epidemiological studies in Canada identified that over 30% of individuals who played sports as children or adolescents reported suffering concussions or suspected concussions, with half of these individuals never being formally diagnosed (Angus Reid Institute, 2015). This finding supports the idea that epidemiological data for concussion rates are generally considered to be far lower than the actual incidence rate as many people do not seek medical attention when they receive concussions (McCrea, Hammeke, Olsen, Leo, & Guskiewicz, 2004).

### *5.3.1 Developmental Sensitivity of Executive Systems to Damage*

Executive functions are broadly understood to be an integrated system of complex cognitive processes that govern flexible, goal-directed behavior and are reliant on subordinate processes like inhibitory control, updating working memory, and shifting attention (Diamond, 2013). Akin to a machine with many moving parts, executive functioning relies upon an interconnected system of frontal-parietal regions and subcortical pathways. Like a complex piece of machinery, there are simply more pieces or places where something could go wrong and this leads to an increased vulnerability to damage in the executive system as it predominantly relies upon whole-brain integrity. Indeed, executive functions and associated brain regions are disproportionately impacted by neurological insults.

Relative to adults, children, and adolescents are considered to have weaker executive function; however, if taken from a neurodevelopmental lens, this difference should be considered normative as opposed to pathological. The beginnings of executive control can be observed as early as 12 months and as children age, they progressively show improvements on measures of executive function, beginning to perform at approximately adult levels by adolescence (Crone, 2009; Jurado & Rosselli, 2007). Unlike in adults, where the executive system is assumed to be fully formed and therefore more robust in the face of neurological damage, there is an even greater vulnerability for developing executive deficits in children and adolescents as maturational brain processes (e.g., synaptic pruning) are underway and are easily altered or disrupted by environmental factors like traumatic brain injury.

Due to the extended developmental trajectory of executive functions, deficits may not be observed until later ages when certain abilities that are expected to develop, fail to emerge (Ashton, 2010; Chapman & McKinnon, 2000; Gil, 2003; Li & Liu, 2013). In a study following 433 children with mild-to-severe TBI or orthopedic injury controls, the proportion of children aged 5–15 with observed executive dysfunction doubled for mild TBI and tripled for moderate-to-severe TBI 3 months after baseline. Indeed, in that same study, observable deficits in executive functioning were seen via parental reports on the BRIEF in up to 40% of pediatric TBI cases within a year of injury, despite relatively few differences with non-TBI controls at baseline (Sesma, Slomine, Ding, & McCarthy, 2008). The neurocognitive foundations for executive functioning are laid in early childhood but not fully realized until adulthood; and in recognition of this increased vulnerability even for the mildest of neurological insults, contemporary injury management protocols for mild traumatic brain injuries like concussion tend to be more conservative for youth than for adults and err on the side of caution (Lumba-Brown et al., 2018; McCrory et al., 2017). Any damage or disruption to the development of executive functioning is a matter of great concern as executive deficits observed in childhood are predictive of a variety of outcomes ranging from reduced individual quality of life to increases in community-level public safety concerns (Diamond, 2013; Moffitt et al., 2011).

### *5.3.2 Pediatric TBI: In a Nutshell*

When examining the current literature on TBI and executive functioning in pediatric populations, there appear to be two general rules governing the relationship between the two:

(1) Any neurological insult impacting the general integrity of brain structures will cause some degree of executive impairment, with degree of impairment scaling with severity of injury and;
(2) Earlier injuries are associated with both worse outcomes and longer-lasting executive deficits, while acknowledging that there are certain critical periods of cortical development that potentially represent times of even greater vulnerability within an already vulnerable group.

Upon reading these two points, one might ask: Why are children at such a risk for developing deficits in executive functioning after TBI? The answer lies in the physical proportions of children and the physical properties of their developing brains. Compared to adults, children have disproportionately large and heavy heads while simultaneously having relatively underdeveloped neck muscles. This combination leads to children experiencing a greater magnitude of overall head movement (e.g., greater whiplash effects) when struck by a forceful impact, which elevates their risk for not only suffering a brain injury but a more serious one. Furthermore, children have thinner skulls and in the case of infants, cranial bones that have yet to fuse together. This leads to an added risk of fractures and increased force applied directly to the brain; and by extension, the potential for more serious damage to brain tissue. Compounding these risks is the pediatric brain itself, which is more likely to experience axonal tearing due to blood vessel elasticity. These risk factors culminate in a brain that is more likely to sustain whole brain injury as opposed to more focal injuries (Case, 2008). As discussed earlier, whole-brain involvement is necessary for executive functions and more complex injuries at developmentally critical periods will have proportionally greater impact on future functioning. Infants, in particular, fit this description and though these physical attributes become less obvious or pronounced as children age, they still remain relevant risk factors.

### 5.3.3 Severity of Injury and Executive Functioning

Due to the significant damage sustained in severe pediatric TBI, virtually every executive function is impacted. The following domains discussed in this section are among the most commonly affected areas of executive functioning in severe pediatric TBI and to a lesser degree, in moderate and mild TBI.

Attentional processes are one of the more sensitive areas to be impacted by severe pediatric TBI (Babikian & Asarnow, 2009; Gil, 2003; Li & Liu, 2013). Given the relatively early maturation of basic attentional control, age of injury, and follow-up becomes particularly relevant as studies with younger samples may not necessarily show differences between pediatric TBI and control groups that are in the early stages of development on both neuropsychological tasks (e.g., NEPSY Auditory Attention) and rating scales like the BRIEF (Crowe, Catroppa, Babl, & Anderson, 2013; Tonks, Williams, Yates, & Slate, 2011), whereas studies with older samples may demonstrate deficits in the domain due to slowed development of attentional processes (Tonks et al., 2011). In terms of more complex attention, it appears that tasks that measure divided attention (e.g., sustained attention in the Dual Task (Score DT) from the Test of Everyday Attention for Children—TEA-Ch) are more sensitive to TBI than more simple forms of attention (e.g., Sky Search from the TEA-Ch) with individuals impacted by severe TBI performing worse than non-TBI controls, even 5 years post-injury (Nadebaum, Anderson, & Catroppa, 2007). That being said, tasks of processing speed (e.g., Coding or Symbol Search) require some degree of focused attention and are sensitive to severe TBI (Nadebaum et al., 2007).

Pediatric patients who have experienced severe traumatic brain injuries have also been observed to develop secondary attention deficit hyperactivity disorder (ADHD). Children who suffer from any kind of TBI are three times more likely to be diagnosed with ADHD than uninjured peers (Schachar, Levin, Max, Purvis, & Chen, 2004), and it is expected that more severe injuries increase this likelihood. Despite many similarities with developmental ADHD in terms of behavioral presentation, a study comparing the neuropsychological performance of children who develop secondary ADHD due to TBI compared to those already with developmental ADHD and TBI-only controls, found significantly greater planning difficulties weaker working memory, and slow and imprecise divided attention for those in the secondary ADHD group (Ornstein et al., 2014).

Alongside issues of attentional control, difficulties with inhibition are commonly seen in pediatric TBI populations. Crowe et al. (2013), using the NEPSY Statue task, found that any degree of TBI led to significantly more difficulties with sustaining performance with a greater number of errors and lower total scores, even for mild pediatric TBI. In a 2-year prospective study of 65 children with severe TBI, using measures like the Stroop and the Statue task, inhibitory control deficits were observed at 2-years post-injury (Krasny-Pacini et al., 2017). Irrespective of age-at-injury Tavano et al. (2014) found that disinhibition was the main feature of TBI symptomatology when comparing children and adults who suffered from TBI.

Multiple reviews of the literature suggest that pediatric TBI, particularly severe TBI has an impact on working memory and on memory function as a whole (e.g., Ashton, 2010; Babikian & Asarnow, 2009; Gil, 2003; Levin & Hanten, 2005). Performance on measures such as the Children's Memory Scale—Attention and Concentration Index have shown observable deficits up to 2 years post-injury (Krasny-Pacini et al., 2017). Even after 10-years post-injury, deficits are observed in tasks like Digit Span, the Rey Auditory Verbal Learning Task, and Token Test for those impacted by severe pediatric TBI (Horneman & Emanuelson, 2009).

Planning and goal setting are higher-order processes that rely on less complex executive functions like attentional control, working memory, and inhibition. It should be no surprise then that given the impact of pediatric TBI on those foundational processes, that more complex executive functions would be affected as well. Perhaps reflecting the delayed onset of executive problems after TBI, Tonks et al. (2011) found that while children under the age of 10 did not show any deficits in Delis–Kaplan Executive Function System (DKEFS) Tower Test performance compared to controls, differences were found in children older than 10. In a sample of 36 adolescents and young adults who suffered mild-to-severe pediatric TBI nearly a decade prior, large effect sizes were observed for the DKEFS Sorting Task ($d = 0.82$), errors made on the DKEFS Tower Test ($d = 1.43$), and the Rey Complex Figure Task—Copy Condition ($d = 0.82$); in this study, those who suffered moderate-to-severe TBI performed worse than individuals who were diagnosed with mild TBI (Muscara, Catroppa, & Anderson, 2008).

One particularly interesting study used a virtual reality anticipation of consequences task in a sample of typically developing adolescents and adolescents that suffered from moderate-to-severe TBI. These researchers found that those with TBI were less likely to think about long-term consequences and more likely to consider only the immediate consequences of an action (Cook et al., 2013). Perhaps even more telling is a study by Wade et al. (2017) where 153 adolescents with moderate-to-severe TBI were assessed on their problem-solving abilities using the Social Problem-Solving Inventory (SPSI) and Dodge Social Information Processing Short Stories. Not only did this group of adolescents report lower levels of rational problem-solving, but they also reported lower levels of negative problem orientations, impulsivity, and avoidance compared to the mean of the normative sample of the SPSI, indicating a relative disengagement from any problem-solving activity. This self-reporting pattern suggests that those suffering from pediatric TBI may lack awareness or underestimate the challenges of problem-solving. Tangentially related to this point, while there is generally a lack of strong evidence suggesting an increase in aggression after TBI, it is suggested that observed increases in aggression may stem from deficits sustained in areas of social problem-solving (Li & Liu, 2013). Aggression may be also manifested as emotional dysregulation and defensiveness as in Sam's case.

One of the defining characteristics of the executive system is cognitive flexibility and it too is impacted by pediatric TBI. Muscara et al. (2008) observed large effect sizes for Trails B ($d = 1.55$), Colour-Word Interference—Time ($d = 0.85$) and Errors ($d = 0.98$), where those diagnosed with moderate-to-severe TBI performed more slowly and with more errors than those diagnosed with mild TBI. Krasny-Pacini et al. (2017) found that performance on tasks like the Wisconsin Card Sorting Task, Design Fluency, and the total number of trials completed in the Tower of London was most impaired at 3-months post-injury but showed rapid recovery by 12 months post-injury. In examinations of executive dysfunction and pediatric TBI at the behavioral level, the BRIEF has been used in much of the literature and has shown good sensitivity of executive deficits (Crowe et al., 2013; Karver et al., 2012; Krasny-Pacini et al., 2017; Mangeot, Armstrong, Colvin, Yates, & Taylor, 2002; Muscara et al., 2008; Nadebaum et al., 2007). However, the BRIEF is not the only measure that has been used to assess more ecologically valid executive deficits. Using an executive behavior screener derived from the Behavior Assessment System for Children (BASC-2) rating scales, Direnfeld (2017) found that adolescents with mild-to-severe TBI demonstrated greater difficulties in behavioral and emotional control than adolescents with neuropsychiatric or neurodevelopmental conditions.

### *5.3.4 Severe Versus Moderate Pediatric TBI*

Often due to small sample size, much of the research tends to place both moderate and severe pediatric TBI in the same categories for analysis but in studies where this is not the case, differences are often observed. Those who have suffered a severe brain injury in childhood go on to have far more significant deficits and show slowed trajectories of recovery compared to moderate TBI (Babikian & Asarnow, 2009). As demonstrated in a study by Karver et al. (2012), children who suffered from severe TBI continue to exhibit higher levels of parent-reported internalizing and externalizing problems using the CBCL as well as increased executive deficit using the BRIEF two years post-injury, whereas children with moderate or complicated mild TBI were more similar to controls who suffered from orthopedic injuries. Gerrard-Morris et al. (2010) followed a group of 3–6-year-olds who had suffered mild-to-severe TBI or orthopedic injuries as a control, finding that, after 18 months post-injury, the children with severe TBI continued to exhibit greater deficits in cognitive ability on neuropsychological measures like the Stroop or Digit Span and developed (or recover) at a slower rate than the other groups during the study period. In a 4-year prospective study of 189 children suffering from orthopedic injuries or moderate-to-severe TBI, chronic adaptive functioning deficits were observed, with moderate TBI showing fewer deficits than severe injuries (Taylor, Yeates, Wade, Drotar, Stancin, & Minich, 2002). Similarly, a 5-year prospective study of 98 children diagnosed with moderate TBI, severe TBI, or orthopedic injuries not only showed that the degree of executive dysfunction, as rated with the BRIEF, was related to the degree of injury, but also showed pediatric TBI in general leads to a chronic pattern of executive deficits (Mangeot et al., 2002). After 10 years post-injury, compared to severe TBI, individuals who suffered moderate TBI showed less impairment in the domains of attention and working memory, verbal learning and memory, visual organization, and cognitive flexibility (Horneman & Emanuelson, 2009).

### 5.3.5 Mild Pediatric TBI and Executive Functioning

While there is some evidence for the long-term impact of complicated (i.e., more severe) mild TBI on divided attention (Papoutsis, Stargatt, & Catroppa, 2014), in stark contrast to severe or even moderate TBI, uncomplicated mild pediatric TBI is generally characterized by relatively minor executive functioning impairments and few (if any) observable long-term impacts (Babikian & Asarnow, 2009). Those who present with long-term difficulties form only a small subset of the injured population (McCrory et al., 2017; Zemek, Farion, Sampson, & McGahern, 2013). Predicting children who go on to develop lingering concussion symptomatology is difficult, and some measures designed for this purpose, while outperforming physician judgment alone, have modest predictive capacity and require further refinement (Zemek et al., 2016). In fact, external factors may be more relevant in this group in terms of post-TBI symptom presentation. For example, it has been observed that executive difficulties post-TBI only emerged in a sample of preschoolers who had insufficient sleep (Landry-Roy, Bernier, Gravel, & Beauchamp, 2018). Physical exercise has been shown to reduce the overall likelihood of developing post-TBI symptomatology (Chrismas & Rivera, 2016; Grool et al., 2016). As children who suffer from mild TBI tend to recover fully, lingering deficits are generally attributed to environmental or pre-injury factors like genetics, premorbid ability, or family characteristics (Babikian, McArthur, & Asarnow, 2013; Chapman & McKinnon, 2000; Durish et al., 2018; Sesma et al., 2008).

### 5.3.6 Adolescence and mTBI

After discussing the typical findings in pediatric TBI and executive functioning, there appears to be an age-group and injury group that exhibits an atypical trajectory of recovery; adolescents who suffer from mild TBI. Among researchers, there is a general consensus that the foundations for most executive systems are in place by the time a child reaches adolescence, theoretically making executive functioning more resistant to long-term damage; however, and as discussed earlier, our systematic review of meta-analyses examining the effects of mild traumatic brain injury on cognition, identified that adolescents are the most vulnerable to the negative cognitive effects of mild traumatic brain injury and suffered particularly when it comes to executive functioning (Karr et al., 2014b). While these negative effects are far less than what a child might experience in a severe or moderate traumatic brain injury, it does appear for mild TBI at least, and it is adolescents who may be more impacted relative to other pediatric age groups. One may be prompted to ask: What could be the reason for this?

From a developmental perspective, adolescence is a time of physical, social, and neurological change. One of these changes is the finding that cognitive capacities are increasing throughout childhood and into adolescence, and there is an increase in activation within subcortical systems during adolescence, which has implications for emotion processing and regulation (Galvan et al., 2006). It has been suggested that while adolescents have an executive capacity that is similar to adults, their performance is impacted in situations where emotionally salient content is present (Crone, 2009). In support of this developmental executive functioning perspective, Prencipe et al. (2011) found that while performance on executive functioning tasks improved as children age, improvements in less emotionally salient executive functioning tasks (e.g., Stroop task) occurred earlier and were more robust, whereas performance on more emotionally salient executive functioning tasks (e.g., Iowa Gambling Task) did not improve until mid-adolescence. Indeed, it is in areas of emotional or psychological distress where researchers tend to find the most evidence for the impacts of mild TBI in adolescence as opposed to standardized or computerized measures of cognitive functioning (Brooks et al., 2013). Mild TBI may impact an adolescent's ability to modulate their emotions and through this emotional dysregulation, executive function performance is reduced.

## 5.4 TBI in Adults and Executive Functioning

### *5.4.1 Occupational TBI Statistics and Trends*

Occupational TBI, and particularly mTBI, is a burdening and costly issue for employees, employers, and compensation cooperatives. Reports for the province of British Columbia where we are located revealed that of the 4800 annual survivors of TBI, 3800 are estimated to be cases of mTBI (Martin, 2003). Cumulative evidence has demonstrated a group of variables that seem to serve as risk factors for experiencing an mTBI, and consequently, compensation claims, including, gender, age, and field of work. The concussion rates in female employees is about half of the prevalence rate for males, particularly for workers aged 15–24 years. However, the rate of employment of females between the ages of 25 and 64 years is not disparate from that of their counterpart males, demonstrating a higher risk for males to suffer a concussion in our province even when rate of employment by gender is taken into account. In terms of age, within the age range of 25–64, it appears that males aged between of 25–44 years are at a higher risk of occupational concussion. Similarly, a prospective cohort study on Ontarian workers being compensated for mTBI found that most mTBIs (i.e., 80%) involved workers between the ages of 20–49, with a majority of males (i.e., 68.3%) being affected (Kristman et al., 2010). Thus, these prevalence rates may be consistent at least across Canadian regions.

There are also known moderators of the capacity of the injured employee to return to work. For instance, there is a positive correlation between age and the amount of time spent on disability leave from work (Martin, 2003; Kristman et al., 2010). Also, individuals with mTBI holding professional or managerial positions return to work significantly faster than their counterparts in manual/labor occupations. These findings have been consistent across several studies conducted in other samples (e.g., Cancelliere et al., 2014). Despite the steadily increasing reports of mixed-mechanism mTBI (e.g., from falls, sports, motor vehicle accidents), work-related mTBI is prone to both under- and over-diagnosis, because injuries may go unreported, or symptoms unrelated to mTBI may be misattributed to the injury, especially in delayed recovery situations (Chang, Lonbard, & Greher, 2011), making it difficult to have a clear picture of the current statistics.

## *5.4.2 Occupational Versus Sports-Related MTBI in Adults*

### 5.4.2.1 Differences in Cognitive Outcomes

The preponderance of research on mTBI has occurred within athletic settings (Comper, Hutchinson, Magrys, Mainwaring, & Richards, 2010; Dougan, Horswill, & Geffen, 2013), but a large amount of research has also explored non-sports-related mechanisms of head injury and its neurological and cognitive sequelae (Belanger et al., 2005). These injuries have been historically amalgamated into a non-athletic category, often referred to as mixed-mechanism mTBI, with injury etiologies ranging from falls to motor vehicle accidents. Previous research has documented key differences between sports-related and mixed-mechanism injuries, with many variables differentiating athletes from the general population, including fitness and incentives for quick recovery (i.e., return-to-play; Belanger & Vanderploeg, 2005). In turn, although past research has extrapolated from sports-related concussion research into other injury types (e.g., military concussion; Lew, Thomander, Chew, & Bleiberg, 2007), mixed-mechanism mTBI may present as a unique style injury, with unique sequelae compared to sports-related head injury (Karr et al., 2014b). As such, the cognitive effects of mixed-mechanism mTBI (i.e., range: 0.07–0.61) differ from that of sports-related concussion, as these injuries produce smaller acute effect sizes than sports-related head injuries across meta-analyses (Karr et al., 2014b), but persist for much longer following injury (Belanger et al., 2005). The minor head injuries experienced by workers may present unique cognitive outcomes, and further, some of these differences contribute to the discrepancy noted between workers and "general population."

Some of the differences in cognitive performance observed after sports-related concussions versus occupational and mixed-mechanism injuries are associated with executive functioning (Karr et al., 2014b). Cumulative evidence using randomized studies (avoiding self-selection effects) has demonstrated that physical exercise is beneficial to us (Hillman, Erickson, & Kramer, 2008), particularly, to our executive functioning (Chang Labban, Gapin, & Etnier, 2012; Tomporowski, Lambourne, & Okumura, 2011; Verburgh, Königs, Scherder, & Oosterlaan, 2013). There are at least three mechanisms through which physical exercise enhances executive functioning (Best, 2010): (1) the executive demands inherent to the type of goal-directed exercise, (2) the neurophysiological changes induced by exercise, including up-regulation of growth factors such as the insulin-like growth factor-1 (for neuronal growth and survival), and the brain-derived neurotrophic factor (activity-dependent modulator of exercise-induced plasticity), and (3) the greater cardiovascular capacity associated with physical fitness, which enhances the efficiency with which oxygen and nutrients are supplied to the brain. Further, variables moderating these effects include exercise intensity and duration (higher effects for higher intensity and longer duration), type of cognitive task (highest effects on higher-order tasks), and fitness level (higher effects observed for higher fitness level). Most research examining the effects of exercise on cognition focuses on interventions involving acute bouts of physical activity. These effects may be short-lived and not necessarily comparable to the effects of long-term physical activity (Padilla, Pérez, & Andrés, 2014). Thus, researchers have pushed for longitudinal evaluation of the effects of exercise on behavior, cognition, and executive neural systems (Voss, Nagamatsu, Liu-Ambrose, & Kramer, 2011). Positive effects of long-term physical exercise on executive attention (Pérez, Padilla, Parmentier, & Andrés, 2014) and inhibitory control (Padilla et al., 2014) have been demonstrated. Although research is still scarce, differences in executive structural and functional neural connectivity (Huang, Lu, Song, & Wang, 2015; Marks et al., 2007) between athletes and controls have been shown, with most research being conducted in young adult athletes.

#### 5.4.2.2 Differences in Recovery Times

Sports-related concussions present a more rapid average recovery rate than mixed mechanism mTBI. Although athletes typically recover from sports-related concussion within seven days of injury (Belanger & Vanderploeg, 2005), the rate of recovery following mixed-mechanism mTBI appears far less clear. Notably, nearly all cognitive abilities present significant effect sizes following 90 days; however, compensation seeking moderates this phenomenon, with non-forensic participants presenting a more rapid recovery before 90 days (Belanger et al., 2005). Past researchers have posited the existence of a “miserable minority” (Ruff et al., 1994; Ruff, Camenzuli, & Mueller, 1996), a term used to describe a small portion of individuals with mTBI that do not reach full recovery by 90 days. Researchers have debated the existence of such persistent symptoms (Rohling et al., 2011), attributing their existence to, in part, feigned symptoms or limited effort on testing (Rohling, Larrabee, & Millis, 2012). Curiously, merely bringing mTBI to the attention of a head-injured individual actually worsens their neuropsychological performance, even outside of situations involving external incentives and/or low effort (Suhr & Gunstad, 2002, 2005). In turn, concussed individuals may experience expectancy effects and misattribute general fatigue to persistent post-concussive symptoms.

#### 5.4.2.3 Differences in Effort (e.g., The "Sandbagging" Phenomenon)

Malingering following mTBI in litigation settings occurs at a roughly 40% base rate, indicating that nearly half of concussed individuals feign symptoms when involved in compensation-seeking claims (Mittenberg, Patton, Canyock, & Condit, 2002). In athletic settings, effort has inversely affected cognitive performance, where low effort at baseline testing will result in what appears to be a less severe deficit at post-concussion testing (Erdal, 2012). Termed "sandbagging", this technique allows players to quickly return to play following injury, as a coach or sports trainer may misinterpret the athlete as recovered. Contrarily, workers may have less tangible incentives to return to work, benefiting from extended time-off, increased rest, and continued pay. As such, they may present an opposite trend, with limited effort at post-injury testing.

One variable that may have an effect on the motivation of workers to return to work is the presence of posttraumatic Stress disorder (PTSD) symptoms. The context in which an occupational mTBI can occur (e.g., falling off a roof, being struck by an everyday tool) in association with the possibility of near-death experiences may increase the incidence of PTSD symptoms. Unfortunately, the rate at which mTBI and PTSD co-occur appears unclear to date, with estimates ranging from 5 to 39% (Carlson et al., 2011). Early research has identified that PTSD is associated with increased post-concussive symptom reporting following mTBI (Bryant & Harvey, 1999). However, the majority of research on mTBI and PTSD has occurred among active duty soldiers and veterans (e.g., Amick et al., 2013; Nelson et al., 2012; Verfaellie, Lafleche, Avron Spiro, & Bousquet, 2014), with no known studies evaluating posttraumatic psychiatric symptoms following workplace mTBI. A past systematic review evaluating the quality of past concussion research recommended that future researchers use a musculoskeletal or orthopedic injury group for comparison in order to control for the aspects of an injury event extraneous to neurological injury (Comper et al., 2010). These extraneous components of injury likely include the trauma surrounding the event and the sequential pain and hardship of recovering from an injury.

### *5.4.3 Military TBI and Executive Functioning*

Since the United States Department of Defense began tracking the frequency of TBI among Service Members in 2000, 383,947 TBIs have been documented through the first quarter of 2018 (U.S. Department of Defense, 2019). The majority of such injuries are mild (82.3%), with far fewer falling within the moderate (9.7%) to severe (1.1%) range. An entire system of care has been developed within the US Veterans Health Administration (VHA) to address polytrauma, which is inclusive of assessment, treatment, and rehabilitation for mTBI and co-occurring mental health needs (Belanger, Uomoto, & Vanderploeg, 2009). TBI has become a significant area of health care cost within the US VHA. In 2009, veterans with TBI diagnosis had four times the healthcare costs than veterans without TBI, and those veterans with the highest costs had comorbid TBI, PTSD, and pain (Taylor et al., 2012). In 2012, veterans with comorbid TBI and PTSD incurred greater healthcare costs than Veterans with PTSD or TBI alone (Kehle-Forbes, Campbell, Taylor, Scholten, & Sayer, 2017). Specific to mild injury, veterans diagnosed with mTBI in 2010 had two to three times higher VHA healthcare costs than veterans who screened negative for TBI over a 3-year period, with the most service utilization concentrated in mental health (Taylor et al., 2017b).

Because most military TBIs are mild in severity, the majority of TBI research on veterans has focused exclusively on mTBI. A growing emphasis has also focused on blast-related mTBI, which is a unique mechanism of injury among primarily military populations (Cernak & Noble-Haeusslein, 2010; Rosenfeld et al., 2013). Researchers have compared the cognitive sequelae of mTBI due to blast and blunt trauma, finding no empirical differences in outcome (Belanger et al., 2011; Lange et al., 2012; Luethcke, Bryan, Morrow, & Isler, 2011). Nonetheless, multiple studies have specifically examined blast-related mTBI among military samples (Amick et al., 2013; Kontos et al., 2013; Nelson et al., 2012, 2010; Peskind et al., 2011; Scheibel et al., 2012; Shandera-Ochsner et al., 2013; Vakhtin et al., 2013; Verfaellie et al., 2014). The cognitive effects of blast-related mTBI are, at most, subtle, with a recent meta-analysis finding evidence of very small group differences based on cross-sectional studies comparing veterans with and without a remote history of blast-related mTBI (Karr, Areshenkoff, Duggan, & Garcia-Barrera, 2014a). The overall effect size (plus highest density interval in parentheses) was $d = -0.12$ ($-0.21$, $-0.04$). Many specific cognitive domains were rarely measured and did not provide precise estimates of group differences. Executive function was more regularly evaluated and demonstrated an overall effect of $d = -0.16$ ($-0.31$, 0.00). When separated based on executive-related constructs (Karr et al., 2018; Miyake et al., 2000), the only negative effect of blast-related mTBI was observed for set shifting: $d = -0.33$ ($-0.55$, $-0.05$).

Despite the subtle effects of blast-related mTBI on cognitive functioning, the majority of veterans screening positive for TBI report moderate to very severe cognitive complaints, including forgetfulness (83%), poor concentration (76%), slowed thinking, difficulty, organizing, and difficulty finishing things (64%), and difficulty making decisions (55%); and interestingly, these cognitive complaints are common among veterans without TBI as well, but occur at lower frequencies: forgetfulness (68%), poor concentration (62%), slowed thinking, difficulty, organizing, and difficulty finishing things (50%), and difficulty making decisions (43%) (Scholten, Sayer, Vanderploeg, Bidelspach, & Cifu, 2012). A recent study examined subjective change in executive function among veterans with a remote history of mTBI, retrospectively rated on the Frontal Systems Behavior Scale (FrSBe) (Karr, Rau, Shofer, Hendrickson, Peskind, & Pagulayan, 2019). Veterans reported significant increases in executive dysfunction post-mTBI. Only 11% of the sample reported clinically significant executive dysfunction prior to their mTBI, whereas 82% reported clinically significant executive dysfunction following their mTBI. Pre-injury characteristics (e.g., age, premorbid intelligence), injury-related characteristics (e.g., number of blast exposures), sleep quality, and neuropsychological test performances failed to predict subjective change on the FrSBe, and PTSD emerged as the sole independently significant predictor of subjective decline in executive function post mTBI. Another study on Active Duty Service Members found minimal correspondence between post-mTBI FrSBe and objective cognitive performances, but found significant correspondence between post-mTBI FrSBe ratings and depression symptoms (Schiehser et al., 2011). Perceived executive dysfunction following mTBI may be closely related to mental health symptomatology as opposed to objective impairment on executive function tests.

The psychiatric complexity of TBI among veterans makes the injury unique in comparison to other populations that experience PTSD at a lower prevalence. Among veterans of operations Enduring Freedom and Iraqi Freedom, PTSD prevalence has been estimated at 23% (Fulton et al., 2015). It is the most common co-occurring psychiatric disorder among Iraq and Afghanistan Veterans with TBI: 73% of Veterans with TBI had PTSD, 45% had depression, and 22% had anxiety (Taylor et al., 2012). Considering the high comorbidity of TBI and PTSD among veterans, and the high healthcare costs associated with these co-occurring conditions, the effects of mTBI cannot be fully appreciated without closely considering the effects of PTSD as well. When comparing meta-analytic effects of remote blast-related mTBI and PTSD, the significantly greater impact of PTSD on executive function becomes evident. A large-scale meta-analysis on the cognitive effects of PTSD found medium effect sizes for executive functions ($d = -0.45$) and attention/working memory ($d = -0.50$). These effect sizes of current PTSD diagnosis, albeit medium in magnitude, dwarf those effects associated with cross-sectional studies on remote blast-related mTBI (Karr et al., 2014a). Although these conclusions demonstrate a greater impact of PTSD on executive function than mTBI, they do not necessarily indicate that mTBI has no meaningful impact on cognitive functioning or neurological structure.

Traumatic axonal injury is a common neurological injury linked to mTBI (Hurley, McGowan, Arfanakis, & Taber, 2014), and multiple past studies have examined changes in brain white matter associated with a history of blast-related mTBI (Bazarian et al., 2013; Jorge et al., 2012; MacDonald et al., 2013, 2011; Matthews, Spadoni, Lohr, Strigo, & Simmons, 2012; Matthews et al., 2011; Petrie et al., 2013; Sponheim et al., 2011). Some of these past studies have shown evidence for concentrated anterior damage that may be associated with executive function deficits (Jorge et al., 2012; Sorg et al., 2014; Sponheim et al., 2011; Yeh et al., 2013). Despite evidence for potential cognitive and neurological changes associated with blast-related mTBI, the act of disentangling the effects of mTBI and PTSD has been an area of ongoing scientific investigation (Rosenfeld et al., 2013). Researchers have even proposed that mTBI and PTSD possibly involve similar underlying mechanisms, or independent pathophysiological mechanisms that result in a shared symptomatology (Hendrickson, Schindler, & Pagulayan, 2018). Cognitive concerns, often related to both mTBI and PTSD, are common among veterans, and regardless of etiology, evidence-based interventions that reduce such concerns have the capacity to improve quality of life among returning service members. Cognitive rehabilitation interventions have been developed to address such concerns in veterans with mTBI (Storzbach et al., 2017), and other trauma-focused interventions have shown generalized benefits on post-concussion symptoms and cognitive concerns (Wolf et al., 2018). Future interventions that aim to address both PTSD and cognitive functioning may be attractive to veterans seeking to address both mental and cognitive health problems.

### *5.4.4 Executive Dysfunction After Adult TBI*

Among the models that are used to discuss executive functioning (see Chap. 1 for a review), Stuss's approach to the conceptual fractionation of executive components has resonated in the clinical settings, particularly useful in examining the aftermath of TBI affecting the frontal and prefrontal areas. Stuss and his colleagues proposed a conceptualization of executive function that includes an aspect of unity, represented by attention, the cognitive foundation of all other processes, and an aspect of diversity, corresponding to three processes: (1) **energization**, associated with bilateral superior medial regions, is the process of initiation and sustaining behavioral responses, particularly in the absence of external triggers or motivators; (2) **task setting**, associated with left lateral frontal areas, particularly involving ventrolateral regions, is the ability to set a stimulus-response, starting from an a priori association and progressing to a trial and error-based learned association; and (3) **monitoring**, associated with right lateral prefrontal areas, is the process of inspecting the task performance over time, making adjustments to behavior as needed (Stuss & Alexander, 2007). They applied this approach in a review of the literature and concluded that while there is no undifferentiated, unifying, dysexecutive syndrome, lesions to specific regions of the frontal lobes produce specific dysexecutive problems. For instance, damage to bilateral (but mostly right) superior medial frontal areas (and their connection to anterior cingulate cortex and supplementary motor areas), appears to be associated with deficient energization (e.g., apathy, unmotivation, problems with initiation, concentration and task maintenance, verbal fluency, impaired interference control in the Stroop test). Damage to left lateral frontal areas, particularly ventral components, was associated with impaired task setting (e.g., problems with task analysis, setting task criterion toward producing correct responses, set lost in the Wisconsin Card Sorting Test, false-positive responses in memory tests—i.e., identifying non-listed words as correct, false alarms in go/no-go tasks—i.e., incorrect responses to the no-go stimulus, and inability to use verbal task instructions to guide behavior). Further, damage to the right lateral frontal regions was associated with impaired monitoring (e.g., problems with modulation of expectancy and time estimation in reaction time tasks, monitoring of temporal information in self-timed conditions, poor error checking and monitoring performance overtime, double recalls in memory tasks—i.e., recalling the same word twice; Stuss & Alexander, 2007).

Cumulative research has consistently demonstrated the vulnerability of executive functioning to TBI, regardless of the level of severity (Lezak et al., 2012; Roebuck-Spencer & Sherer, 2008), but certainly with large variability on presentation. On mTBI, common executive-related difficulties reported include attentional deficits and difficulty in speed of processing, associated with the diffuse axonal damage commonly observed after mTBI (Krpan, Levine, Stuss, & Dawson, 2007). Our meta-analysis identified that executive functions are the most susceptible to the impacts of multiple mTBIs (Karr et al., 2014b), but there is consensus in that the great majority of cases recover function within 90 days after injury, with neuropsychological testing findings being unable to detect impairments past three months in most cases (Dikmen, Machamer, & Temkin, 2001; Lange, Iverson & Franzen, 2009; Schretlen & Shapiro, 2003). These findings do not vary as a function of positive neuroimaging findings. In the absence of a global reduction in functioning, patients with complicated mTBI show a greater proportion of low scores than the uncomplicated mTBI during the acute phase of recovery (first two months), and these small differences are no longer significant after 3 months (Lange et al., 2009). This report is consistent with Sam's presentation.

A few patients may present with long-term difficulties and persistent post-concussion symptoms, particularly in relation to emotional dysregulation (e.g., anxiety, depression symptoms). There is ongoing examination trying to clarify the nature of this vulnerability to persistence of symptom reporting. A prospective biopsychological study by Wäljas et al. (2015) demonstrated that persistence of symptom presentation was not associated with level of severity of injury (e.g., complicated mTBI) but rather, with a prior history of mental health problems. A longitudinal study by Maruta et al. (2016) examined a group of patients at three months and then at 5 years post-injury and identified that the original mTBI retained associations with lower performance at a statistically significant level, even when variance associated with demographic variables (e.g., gender, race) and the development of depression and PTSD symptoms post-injury was accounted for in the model.

Almost every aspect of executive functioning has been reported as vulnerable to impairment after moderate and severe TBI. Deficits on planning, cognitive flexibility, working memory, attention, processing of information, poor judgment and impaired decision making, reduced capacity for self-evaluation and task monitoring, lack of initiation and motivation issues (e.g., apathy), impaired self-regulation and aggressive behavior, emotional and affect dysregulation, are on the top of the lists (Krpan et al., 2007; Langlois et al., 2006; Lezak et al., 2012; Maas et al., 2008; Roebuck-Spencer & Sherer, 2008; Stuss & Alexander, 2007). Executive dysfunctions are quite impairing and are critical in determining patients' ability to return to independent living and their jobs (Roebuck-Spencer & Sherer, 2008). They are difficult to treat, particularly as one of the key difficulties observed after moderate and severe TBI is impaired self-awareness (Prigatano, 2009). Self-awareness is associated not only with the drive to participate in rehabilitation, but also with empathy and insight (Lezak et al., 2012). As such, it is of great relevance in any intervention aiming to rehabilitate executive functions after TBI. The following section discusses rehabilitation approaches that have been deemed effective in gaining self-awareness and facilitating recovery of function post-injury.

## 5.5 Rehabilitation of Executive Dysfunctions After TBI

Despite the potential multitude of impairments associated with executive functioning following TBI, there are interventions that have shown to be effective for restitution of function. While Miyake and colleagues' (2000) approach offers a well-supported framework for studying executive functions, we will use Stuss' (2011) clinical–neuroanatomical–evolutionary model to lay out the different areas of executive dysfunction following insult to frontal regions in the brain that are commonly observed following TBI. Specifically, we will cover deficits relating to energization, executive cognitive functions, behavioral self-regulation, and metacognitive processes (Stuss, 2011). To address these areas, we will limit our discussion to interventions aimed at regaining self-awareness and remediating attention, problem-solving, and metacognition. Of note, the material in this section will be brief, highlighting only a few of the most used, supported, and promising treatments for executive-related dysfunctions.

### *5.5.1 Awareness Deficits and Associated Intervention Strategies*

Self-awareness is characterized by an individual's ability to recognize cognitive, behavioral and emotional difficulties that may have occurred following brain injury (Crosson et al., 1989). It is common for there to be deficits in self-awareness following TBI, occurring 45–97% of the time (Sherer et al., 1998), and such impairment can be problematic in several ways. Unawareness of one's deficits negatively impacts the course of neurorehabilitation (e.g., of executive functioning), through its impairment of volition (Lezak et al., 2012), often reducing the effectiveness of treatment through noncompliance. It can be either neurogenic (i.e., anosognosia) or psychological (i.e., defensive denial), or some combination of both, with no existing gold standard assessments to discriminate between the two (Prigatano, 2005). Self-awareness can fluctuate throughout the course of rehabilitation, even moment to moment, and should therefore be frequently assessed in order to determine appropriate treatment.

Although empirically supported interventions for self-awareness deficits are lacking (Cicerone et al., 2005), we will briefly discuss two of the most commonly applied approaches. Giacino and Cicerone (1998) proposed a variety of interventions for different types of unawareness. For unawareness that is due to a specific cognitive deficit, intervention should target such deficit. In cases of amnesia, for instance, this could entail incorporating reminders about one's impairment. For dense unawareness due to organic brain dysfunction (i.e., anosognosia), treatment could entail structuring the environment to minimize the deficit, or training in task-specific routines (e.g., using procedural memory) without reliance on appreciation of deficits. Lastly, Giacino and Cicerone (1998) recommend that to treat unawareness from psychological (defensive) denial, a combination of supportive psychotherapy and other techniques like motivational interviewing could be effective; here, discrepancies between perceived abilities and actual performance should be gently highlighted.

Crosson and colleagues (1989) proposed a tripartite, hierarchical model of awareness, its deficits, and related recommended interventions (see Table 5.1). For impairment in *intellectual* awareness, which is the knowledge that one has a particular deficit, they recommend providing psychoeducation through review of materials such as medical charts, neuroimaging, and brain injury fact sheets. To treat deficits in *emergent* awareness, which is the more complex ability to recognize a problem as

**Table 5.1** Awareness types (according to Crosson et al., 1989), cognitive domains influencing EF, and corresponding intervention strategies

| **Type of awareness** | **Impairment** | **Intervention** |
|---|---|---|
| Intellectual—acknowledging that one has a particular deficit | Patient has not been told, or cannot remember, understand, or conceptualize that they have a particular deficit | Provide psychoeducation through review of neuroimaging, medical chart notes, brain injury fact sheets, etc |
| Emergent—recognizing a problem (due to their deficit) as it occurs | Patient understands they have a deficit, but is not aware of the problem "in the moment" | Experiential; error prediction and monitoring |
| Anticipatory—knowing where/when a problem is likely to occur, and planning to minimize its occurrence | Patient cannot make accommodations or compensations for a problem due to lack of skill-knowledge in implementing an appropriate plan | Train task-specific routines through procedural learning or metacognitive strategies (focus of traditional EF rehabilitation interventions) |
| **Cognitive domain influencing executive functioning** | **Impairment** | **Intervention** |
| Attention | Patient has difficulty concentrating on a task, often getting sidetracked | *Mindfulness training (MT)*: self-directed attention regulation through focused attention and open monitoring |
| Metacognition | Patient has difficulty carrying out a task, making several mistakes | *Self-instructional training (SIT)*: verbalization of thought process during task<br>*Metacognitive skills training (MST):* explicit reflection of performance during task, and generation of solutions to encountered obstacles |
| Problem-solving | Patient has difficulty carrying out a task, making several mistakes | *Goal management training (GMT)*: formulation of steps to reach a goal, followed by frequent monitoring of action-goal congruency |

it occurs, error prediction and monitoring may be beneficial. In addition, the experiential techniques may simply be effective, such as the experience of undergoing neuropsychological testing. Lastly, the most complex type of awareness that Crosson and colleagues (1989) propose is *anticipatory* awareness, which is undergoing planning to minimize the occurrence of deficits. Impairment in this area might benefit from training of task-specific routines through procedural learning or metacognitive strategies.

### 5.5.2 Attention Training

As with awareness, attention heavily influences higher-level executive functioning, thus making it an important area for rehabilitation following TBI. A recently developed intervention for attention that has shown promise is mindfulness training (MT). Self-directed attention regulation, specifically, is a major component of MT. MT typically begins with sessions involving focused attention, where an individual attempt to direct their attention toward a specific object. Often times, focused attention might be directed toward an individual's body (e.g., their lower abdomen), while they attempt to tune out external distractors. Following focused attention, individuals may practice open monitoring, in which they allow themselves to be aware of all experiences, external or internal, responding to sensations and thoughts with an open, receptive and non-judgmental attitude (Fox et al., 2014). MT allows for ecologically relevant practice and has several aims, including improvement of self-monitoring and attention.

The efficacy of mindfulness practices has recently been supported in the literature. A meta-analysis by Sedlmeier and colleagues (2012) found mindfulness meditation to be generally associated with medium effect sizes on attention. Further, mindfulness training has shown promise for individuals who have experienced a brain injury. In a pilot study conducted by Azulay and colleagues (2013), 22 patients who experienced a mild TBI underwent a 10-week program of mindfulness-based stress reduction (MBSR), a type of mindfulness practice involving body scans (i.e., somatically focused mindfulness practice), sitting and walking meditation, and yoga (Azulay, Smart, Mott, & Cicerone, 2013). Results demonstrated significant improvement in measures of attention, including sustained attention and attentional control.

### 5.5.3 Metacognitive Strategy Training

While behaviorally training patients to perform specific tasks involving executive functions (e.g., planning, sequencing, and organization) can be effective, metacognitive strategy training can have a more overarching and generalizable impact by improving executive functions themselves. Metacognition likely represents the most highly developed of the executive functions. Often defined as "thinking about thinking," metacognition relates to an individual's ability to self-monitor and evaluate, have appreciation of their abilities and limitations, and be able to flexibly implement strategies and supports when they are operating within an area of relative weakness. As such, interventions in the area of metacognition typically involve training in self-monitoring and self-regulation. Compared to behavioral training aimed at executing specific tasks, metacognitive strategy training requires a greater degree of awareness on the part of the individual.

A commonly used, and empirically supported, technique for metacognitive training is self-instructional training (SIT). Initially developed by Donald Meichenbaum for use with children, (e.g., Meichenbaum & Goodman, 1971), SIT involves explicitly verbalizing the problem-solving process as a means to make one's "thinking about thinking" more overt. This would include verbalizing what one is doing, how one is moving through the various steps, guiding oneself when the task at hand becomes difficult, and reinforcing oneself for task completion. Studies examining SIT have found it to be a particularly effective treatment following acquired brain injury (like in TBI), involving executive deficits, finding significant decreases in task-related errors and task-irrelevant behaviors (Cicerone & Giacino, 1992; Cicerone & Wood, 1987). However, Dawson and colleagues (2009) found that SIT might be better suited for specific tasks, as this approach did not appear to be effective for participants in their study who had more complex task goals.

In terms of other metacognitive interventions, a study was conducted by Ownsworth and colleagues (2010) to examine the impact of metacognitive skills training (MST) in error self-regulation following TBI (Ownsworth, Quinn, Fleming, Kendall, & Shum, 2010). Here, MST involved explicit reflection on prior performance of making a meal, errors made, and how those errors might be averted in the future. Individuals were also encouraged to generate their own solutions to problems rather than relying on therapist input. Results showed that individuals who underwent MST showed a significant reduction in the frequency of both errors made and checks (i.e., asking for therapist advice), and a significant increase in self-corrections from baseline (Ownsworth et al., 2010).

### *5.5.4 Problem-Solving Training*

As per our opening case, Sam was recommended a problem-solving approach to her rehabilitation of the lingering executive impairments observed during the neuropsychological assessment. Problem-solving rehabilitation incorporates aspects of both attention and metacognitive training. Several interventions have been developed to train individuals with TBI-related executive dysfunctions in structured, systematic approaches to problem-solving. However, we will focus on the most well-known, and hitherto most empirically supported, treatment: goal management training (GMT; Levine et al., 2000, 2011; Novakovic-Agopian et al., 2010). This intervention was theoretically derived based on Duncan's (1986) theory of goal neglect (i.e., failure to maintain action in service of goals) following frontal brain injury. GMT is a five-stage process that involves (1) directing attention toward a goal, (2) selection of a particular goal, (3) parsing that goal into steps or sub-goals, (4) learning the necessary steps, and (5) during the implementation of these steps, continually monitoring to ensure that the outcome of action matches the desired goal. In this last step, patients are trained to stop their action, focus (i.e., return from mind-wandering), and check that their action is goal-relevant (often referred to as “updating their mental blackboard”). To assist with the focusing aspect, patients practice mindfulness aimed at improving their attention. These stages are repeated in an iterative fashion wherever there is a mismatch between the current action and the goal to be accomplished (Levine et al., 2000).

Like metacognitive strategy training, GMT provides the patient with generalizable skills that can be applied to any novel problem-solving situation, greatly increasing the likelihood of transfer of training to different contexts. Aside from helping with problem-solving, GMT can be useful in developing anticipatory awareness, where individuals recognize that they have a problem-solving deficit and work proactively to implement plans to approach that problem if and when it arises. However, like metacognitive strategy training, GMT and other problem-solving approaches are limited in that they require an awareness of deficits, at least at the intellectual level, in order for the strategies to be effective, as well as motivation to implement behavioral changes.

GMT has received empirical support for its effectiveness. A recent meta-analysis by Stamenova and Levine (2018) examined the effectiveness of GMT in various clinical samples, including TBI. Specifically, they looked at how well GMT treated cognition in a multitude of domains, including executive functioning, speed of processing, long-term memory, subjective ratings, and functional tasks like instrumental activities of daily living. They found that GMT produced small to medium effect sizes for all cognitive domains except for processing speed and that these effects were maintained at follow-up, except for subjective ratings. Medium effects were seen specifically for executive functioning tasks (Stamenova & Levine, 2018). Further support for GMT has come from a systematic review by Krasny-Pacini and colleagues (2014), who examined the problem-solving treatment in patients recovering from brain injury (Krasny-Pacini, Chevignard, & Evans, 2014). They found that comprehensive treatment plans including GMT, while integrating other approaches, are effective in executive function rehabilitation. However, they determined that there is not sufficient evidence yet to support GMT as an effective stand-alone treatment (Krasny-Pacini et al., 2014).

In summary, cognitive rehabilitation interventions can treat a variety of executive-related dysfunctions in people who have experienced a TBI. This chapter section discussed a handful of techniques targeting impairments in awareness, attention, metacognition, and problem-solving (summarized in Table 5.1). For deficits in awareness, various techniques can be employed depending on the type of awareness affected; these can range from reminder and psychoeducation about one’s deficits to task-specific training and use of metacognitive strategies. Mindfulness training has shown some promise in treating attention, specifically sustained attention, attentional control and self-monitoring. Two types of interventions that have been supported for treating metacognition are self-instructional training (SIT) and metacognitive skills training (MST), both of which have helped improved task performance. Similar to metacognitive training, goal management training (GMT) has been effective in improving problem-solving skills, emphasizing a stepwise approach for selecting and attending to goals.

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