The mnemonic consequences of moderate-to-severe traumatic brain injury

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Abstract

This chapter presents a review of the effects of moderate-to-severe traumatic

brain injury (TBI) on various aspects of memory, including working memory,

episodic and semantic memory / contextual memory, prospective memory, skill

learning and memory self-awareness. In addition to reviewing the cognitive

sequelae of TBI, we discuss approaches to memory assessment in TBI and

memory remediation. TBI inflicts diffuse injury, including to the white matter

(diffuse axonal injury), which is reflected in heterogeneous patterns of impairment

across participants. Further, neuroimaging findings consistently demonstrate the

vulnerability of the frontal lobes. This vulnerability is expressed in the pattern of

memory impairment characterizing this population as emerges in this review.

Memory processes that require strategic and effortful elaboration appear

particularly susceptible to TBI. By focusing on these processes, the sensitivity of

memory assessment and the efficiency of memory remediation could benefit

significantly.

Keywords: Traumatic Brain Injury (TBI); Memory impairments: Frontal lobes

TBI has become a significant health problem in modern industrialized countries. Based just on data gathered in 2013, the Centers for Disease Control and Prevention (CDC) reported that 2.8 million people in the U.S. alone suffered from traumatic brain injury (TBI), including 282,000 TBI-related hospitalizations and approximately 56,000 TBI-related deaths in one year (Taylor, Bell, Breiding, & Xu, 2017). Severity of injury following TBI is typically based on three measures: 1. Glasgow Coma Scale (GCS), which is used to assess a person's level of consciousness, with scores ranging from 3-15. 2. Post Traumatic Amnesia (PTA), a state of disorientation and confusion following TBI and 3. Length of coma. *Severe* TBI is characterized by GCS from 3 to 8, PTA more than 7 days (Williamson, Scott, & Adams, 1996), and length of coma greater than 36 hours. Moderate injury is characterized by GCS from 9 to 12, PTA 1 to 7 days, and length of coma between 20 minutes and 36 hours. Mild TBI is characterized by GCS 13-15, PTA less than 24 hours, and coma less than 30 minutes (McKee, & Daneshvar, 2015; Williamson et al., 1996). According to Dewan et al. (2018), 81% of all reported TBIs are considered mild, 11% are considered moderate and 8% are considered severe.

TBI causes a wide range of emotional, behavioral and cognitive difficulties. It is associated with high mortality rates and multiple functional deficits, including occupational, social, mental, and physical health problems (Andelic, Sigurdarottir, Schanke, Sandvik, Sveen, & Roe, 2010; Azouvi, Arnould, Dromer, & Vallat-Azouvi, 2017). Memory impairment is one of the most disturbing consequences of such an injury, due to its effect on a wide range of everyday activities, employability, and social interactions. Jourdan et al. (2016) reported that memory problems were the

most frequent complaint (67.5%) four years after acquiring TBI. Nash et al. (2014) found that a year after injury, 60.4% of motor vehicle accident victims who suffered moderate-to-severe TBI complained of memory difficulties. On the one hand, the prevalence of TBI patients across the population, together with patients' availability in rehabilitation centers, enables extensive research on this population. On the other hand, due to the diffuse nature of their injuries, TBI patients are not the ideal group to study brain-behavior relations. Literature on the effect of TBI on memory has already been reviewed in several articles and book chapters (Azouvi et al., 2017; Canty, Shum, Levin, & Chan, 2014; Goldstein & Levin, 1995; Vakil, 2005, 2013). However, due to ever-changing technologies and procedures, along with new theoretical conceptualizations of memory, a continuous update of such literature reviews is necessary.

Neuropathology following traumatic brain injury (TBI)

Neuroimaging acquired following TBI is usually either computerized tomography (CT) scan or more recently, magnetic resonance imaging (MRI). This imaging provides qualitative information about the clinical situation and the severity of the patient's injury (Bigler, 2016). Structural MRI studies have reported that the brain structures most vulnerable to damage following TBI are the frontal and temporal lobes (Avants et al., 2008; Bigler, 2013; Stuss, 2011). These regions are most vulnerable "because of how the brain is cradled in the anterior and middle cranial fossae, and the resulting consequences of how the brain strikes and/or deforms against bony ridges and internal surfaces of the cranial vault" (Bigler & Maxwell, 2011) (p. 67). Bigler and Maxwell (2011) also reported brain atrophy following TBI, expressed by expansion of the ventricles. Atrophy of the hippocampus following TBI has been

associated with poor memory performance (Bigler, Johnson, Anderson, & Blatter, 1996). In addition to these cortical injuries, lesions to white matter, expressed as a diffuse axonal injury (DAI), are also common, especially following moderate-severe TBI (Spitz, Maller, O'Sullivan, & Ponsford, 2013). White matter integrity is vulnerable to rapid acceleration/deceleration of the brain following motor vehicle accidents, a common cause of TBI. This is the primary cause of DAI following TBI (Johnson, Stewart, & Smith, 2013).

These white matter lesions interfere with the widespread connectivity among the frontal, temporal and parietal lobes, and various subcortical structures. White matter lesions can occur in almost every brain region and are correlated with injury severity (Levine, Kovacevic, Nica, Schwartz, Gao, & Black, 2013). DAI also results in significantly slowed cognitive processing (Caeyenberghs, Verhelst, Clemente, & Wilson, 2017). Diffusion tensor imaging (DTI) is frequently used to assess DAI by measuring the anisotropic diffusion of water molecules (Hunter, Wilde, Tong, & Holshouser, 2012). These DTI studies probably demonstrate best the diffuse nature of TBI.

TBI victims show widespread and more diffuse activity of brain areas, indicating re-organization as well as compensatory over-activation and engagement of various brain networks (Bigler, 2013). Additionally, edema and ischemia further complicate the functional outcome of TBI. Long-term follow-up studies on TBI victims has revealed brain atrophy, apoptosis, inflammation, microgliosis, loss of myelin and cerebral blood flow changes (Bramlett & Dietrich, 2015). This diffuse nature of TBI could explain the variability in cognitive and behavioral dysfunction reported in this disorder. A promising approach that could help understand this variability has been

introduced recently. Bigler (2016) presented the "system biology approach" for the study of the relationship between neuropathology following TBI and its neuropsychological consequences. The assertion of this approach is that various neuroimaging methods (including structural and functional techniques, e.g., MRI, fMRI, PET, SPECT, MEG, EEG, etc.) may be more sensitive to different pathologies expressed in various neuropsychological impairments. Such an integrative strategy has the potential to better predict and explain the specific cognitive and behavioral consequences of TBI based on a detailed profile of the nature of the injury. Notwithstanding the above, consistent findings that the frontal and temporal lobes are most vulnerable following TBI (Avants et al., 2008; Bigler, 2013) lead to a quite consistent pattern of memory impairment: memory processes that require strategic and effortful elaboration either at encoding or at retrieval phases of memory (see Vakil, 2005).

Cognitive implications of TBI

TBI affects a wide range of cognitive processes, including but not limited to human memory. A meta-analysis conducted by Schretlen and Shapiro (2003) found that despite improvement in overall cognitive performance throughout the first two years post moderate-to-severe TBI, patients remain severely impaired compared to controls. Most prominently, TBI results in impaired executive functions, attention and speed of processing (Azouvi, Vallat-Azouvi, & Belmont, 2009). These deficits often accompany and affect the way memory deficits are expressed following TBI. Hence, memory impairment following TBI is not always a pure deficit, as it may be indirectly affected by impaired cognitive processes known to interact with memory.

Executive functions: Damage to the frontal lobes can cause impairments in the executive functions of self-directive behavior, planning, decision-making, judgment, self-perception and self-monitoring (Tranel, Anderson, & Benton, 1994). Gansler, Covall, McGrath, and Oscar-Berman (1996) reported that patients with TBI had impaired executive functions, as determined by the Wisconsin Card Sort Test (see also review by Stuss, 2011). Draper and Ponsford (2008) reported that executive function was impaired even 10 years following TBI, and that it was associated with severity of injury. Using Moscovitch's (1994) terminology "working-with-memory", the frontal lobes support the memory system by applying top-down processes such as implementation of strategy, organization, and conceptual elaborative encoding and retrieval.

Attention: Attention is not a unitary system, but rather is composed of several sub-processes (Posner & Petersen, 1990; see, also Chapter X.Y, "Attention and Memory" by Sherman and Turke-Brown). Individuals with moderate-to-severe TBI have difficulties with selective attention (Schmitter-Edgecombe & Kibby, 1998), divided attention (Leclercq et al., 2000), and sustained attention (Dockree, Kelly, Roche, Hogan, Reilly, & Robertson, 2004). Slovarp, Azuma, and LaPointe (2012) found that impaired working memory (WM) was associated with sustained attention measures. A meta-analysis conducted by Mathias and Wheaton (2007) confirmed that TBI affects all aspects of attention. Mangels, Craik, Levine, Schwartz and Stuss (2000) interpreted a disproportionately large effect of divided attention on memory in TBI as expressing the influence of attention deficits on memory impairments.

Speed of processing: Felmingham, Baguley, and Green (2004) demonstrated a direct relationship between DAI in TBI patients and processing speed. WAIS-III processing speed index scores were found to be sensitive to TBI (Axelrod, Fichtenberg, Liethen, Czarnota, & Stucky, 2001; Fisher, Ledbetter, Cohen, Marmor, & Tulsky, 2000). Madigan, DeLuca, Diamond, Tramontano, and Averill (2000) used two serial addition tests (visual & auditory) to show that individuals with TBI were significantly slower in performing the task even when controlling for accuracy. Based on meta-analysis, Ferraro (1996) concluded that patients with TBI are significantly slower than controls on cognitive tasks involving simple and choice-reaction time. Also based on meta-analysis, Mathias and Wheaton (2007) found that TBI significantly affects information-processing speed. Draper and Ponsford (2008) reported that processing speed was impaired even 10 years after TBI, and that it was associated with severity of injury.

Memory assessment

Vakil (2013) distinguished between three different memory assessment methods used to evaluate memory following TBI. The first method has an experimental design; it typically addresses a theoretical question and attempts to isolate a particular memory process. An example would be studies investigating the effect of TBI on various aspects of context memory or skill learning (see the corresponding sections). The second is a more general approach: memory is assessed as a component of neuropsychological evaluation following TBI. This method's primary objective is to characterize the effect of TBI on various aspects of memory. It often involves the administration of standardized memory batteries (e.g., the *Wechsler Memory Scale*) or specific tests tapping various aspects of verbal learning and

memory, such as the Rey-Auditory Verbal Learning Test (AVLT) (Vakil &

Blachstein, 1997), the California Verbal Learning Test (CVLT) (Delis, Kramer,

Kaplan, & Ober, 1987) and the Selective Reminding Test (Buschke & Fuld, 1974).

Vakil (2012) classified the various commonly assessed measures of memory into

several dimensions: Timeframe, modality, process, and retrieval conditions (see

Figure 1). The third method evaluates memory assessment by using clinically driven

questions concerning rehabilitation or daily functioning; this design typically

encompasses stronger ecological validity. Tests generally use real life tasks and items

(e.g., Rivermead Behavioral Memory Test –RBMT; Wilson et al., 1985). According

to Vakil (2013), these three approaches can be viewed as a continuum mirroring a

tradeoff between the evaluation of a purer memory process with low ecological

validity or vice versa. In recent years, there has been an increase in the use of a virtual

reality (VR) setting for neuropsychological assessment, including memory assessment

(Corriveau-Lecavalier, Ouellet, Boller, & Belleville, 2018). VR has the advantage of

better simulating the real world, thus increasing the assessment's ecological validity,

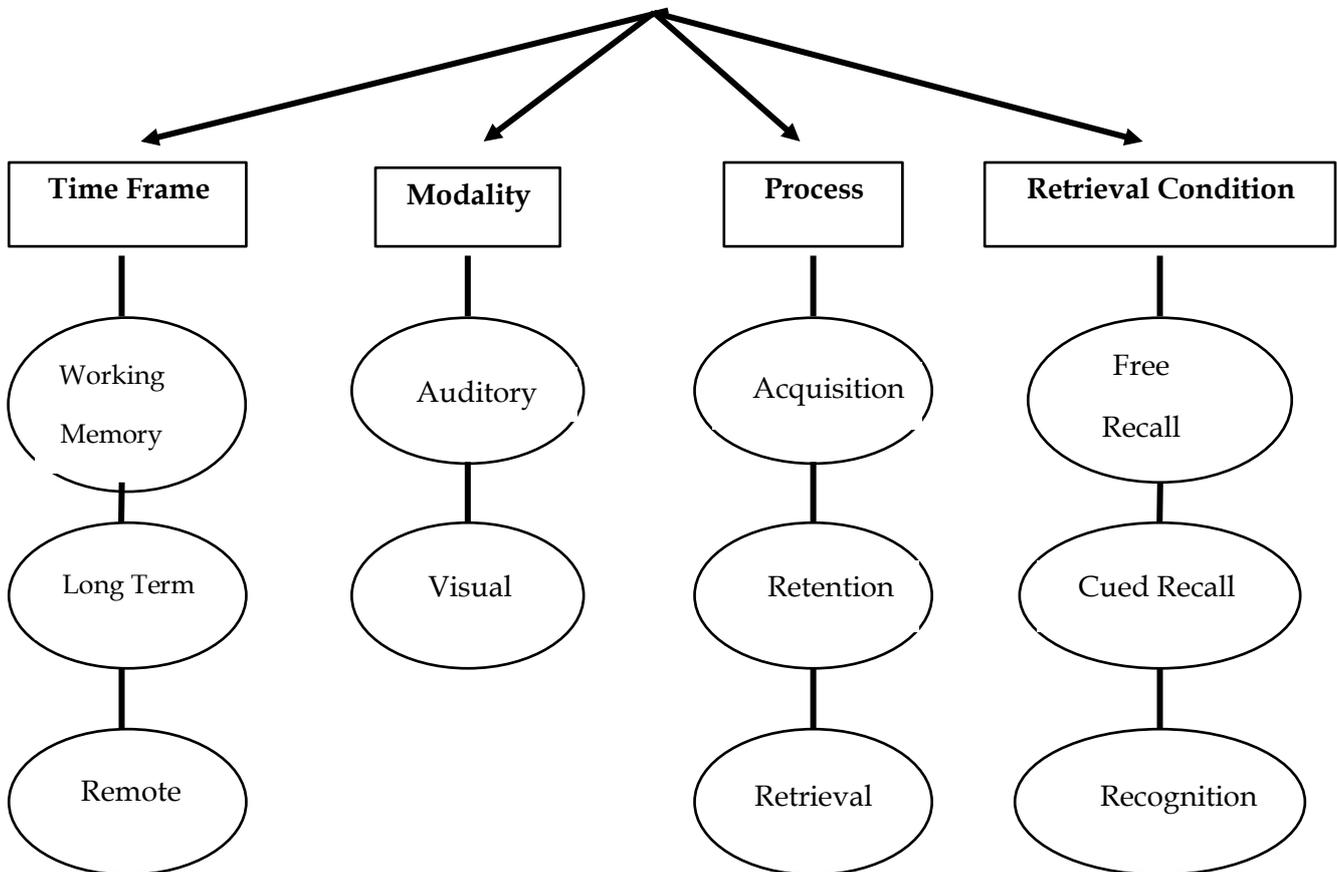in addition to allowing for control and recording of all task parameters.

Memory Measures

Figure 1: Variety of memory measures (adopted with permission from Vakil, 2012)

Working memory

Baddeley (2003) proposed a revised version of his influential multi-component model of WM. According to this model, a central executive orchestrates the operation of two slave systems: a phonological loop and a visuospatial sketchpad. The central executive bears responsibility for controlled and attentional processes, divided attention and the manipulation of information. The modality-specific slave systems bear responsibility for maintenance and rehearsal of information in verbal and visual modalities. The episodic buffer is the additional component in the revised

version of Baddeley's WM model, serving as a multidimensional store that integrates all components of WM with long-term memory.

Vallat-Azouvi, Weber, Legrand, and Azouvi (2007) conducted one of the few studies that simultaneously assessed multiple components of Baddeley's WM model. They demonstrated that patients with severe TBI performed similarly to controls on tasks involving the so-called slave systems, such as the digit span test for the phonological loop and the Corsi Block-tapping test for the visuospatial sketchpad. In contrast, patients were significantly impaired on a variety of tests involving the central executive system (e.g., the Brown Peterson paradigm), particularly under interference. Several studies have reported errors during dual-task paradigms for TBI patients, which have been interpreted as an indication of poor central executive system functioning (Anderson & Knight, 2010; Asloun et al., 2008). They found that participants following TBI exhibited impaired performance on several tasks involving the central executive system, such as the random generation task (Azouvi, Jokic, Van der Linden, Marlier, & Russel, 1996) and the n - back task (Kasahara et al., 2011). Dunning, Westgate and Adlam (2016) conducted a meta-analysis of 21 studies testing WM in individuals with moderate-to-severe TBI. They reached three major conclusions: Firstly, verbal and visuospatial WM are impaired following TBI compared to controls, which they interpreted as a reflection of damage to a more general mechanism - the central executive system. Secondly, as time following onset increases, so does the severity of verbal WM, suggesting that these functions do not recover over time. In fact, the opposite is true, they deteriorate over time. Thirdly, the older the individual at the time of onset, the poorer the verbal WM performance. This

finding supports the plasticity hypothesis, which proposes that the earlier in life the injury, the better the chances of recovery.

Christodoulou et al. (2001) tested individuals with moderate-to-severe TBI on a WM task - a modified version of the paced auditory serial addition task (PASAT). Participants listened to a sequence of numbers and were asked to continuously add up the last two consecutive numbers. The processing required in this task is assumed to involve the central executive system. Behavioral results showed that TBI patients made more errors than controls. Functional neuroimaging data indicated that although similar brain regions were activated (i.e., frontal, temporal, and parietal lobes) for both groups, for the TBI group, overall activation was more dispersed and lateralized to the right hemisphere, compared to controls. The authors suggested that this was because patients recruited more brain areas in order to deal with the demanding task. Palacios et al. (2011) tested several measures of WM for individuals with TBI, including the n – back task. Researchers found a correlation between WM measures and white matter integrity measured by DTI (superior longitudinal fasciculi, corpus callosum, arcuate fasciculi and fornix). A neuroimaging study by Merzagora, Izzetoglu, Onaral, and Schultheis (2014) of individuals with TBI used functional near-infrared spectroscopy (fNIRS) while testing WM with the n - back task. Although performance of the TBI and control groups did not significantly differ for the n - back task, brain activation measured with fNIRS differed across the two groups. Overall, brain activation, particularly in the dorsolateral prefrontal cortex (DLPFC), was higher for the TBI group than the control group. The researchers suggested that this reflected increased recruitment of such areas to enable coping with the task. In a longitudinal study using fMRI, Sanchez-Carrion et al. (2008) demonstrated an initial

low activation of the right superior frontal gyrus for the TBI group compared to that of the controls while performing the *n* - back task. The difference between the groups had decreased six month later. Furthermore, this recovery was associated with improvement on the task performance. Thus, the central executive is consistently reported to be more vulnerable than the slave systems to the effects of TBI. This is consistent with previous findings, demonstrating that the central executive involves the frontal lobes, primarily the dorsolateral prefrontal cortex (Baddeley, 2003), which is vulnerable following TBI (Avants et al., 2008; Bigler, 2013; Bigler & Maxwell, 2011; Stuss, 2011).

Episodic and Semantic Memory

Episodic memory refers to memory for events typically bound contextually to a person, time and place (see Chapter X.Y by Ranganath). In contrast, semantic memory (see Chapter X.Y by). refers to general knowledge that is not bound to a specific context. Autobiographical memory, which is memory about oneself and personal experiences, can be categorized as episodic memory although it may also contain semantic information (see Chapter X.Y). Note that memory tasks are not pure and might involve both episodic as well as semantic memory. Therefore, the distinction between episodic and semantic memory is not always clear cut. Furthermore, it is important to distinguish between *semantic memory* as defined by Tulving (1972) as general knowledge not bound to specific context, and *semantic processes* which involve elaboration of the information, including processes such as categorization or formation of semantic associations between various units of information.

Episodic memory and semantic processing: Learning and forgetting processes interact with each other, since the quality of learning affects the forgetting rate, and forgetting impacts measures of the rate of learning. Therefore, these two aspects of memory are presented together. Learning rate is commonly measured by tests in which verbal or visual information is presented in repeated trials. Frequently used verbal learning tests include the Rey-AVLT (Vakil & Blachstein, 1997), the CVLT (Delis et al., 1987) and the Selective Reminding Test (Buschke & Fuld, 1974). In addition to these common tests, the Shum Visual Learning Test (Shum, Harris, & O'Gorman, 2000) is sometimes administered to individuals with TBI to assess the learning rate for visual stimuli. The advantage of these tests, usually used in clinical settings, is that they tap several measures of memory and learning. For example, the Rey–AVLT can generate several measures such as immediate memory, learning rate, proactive and retroactive interference, retention over time and retrieval efficiency (Vakil, Greenstein, & Blachstein, 2010). Unfortunately, all these measures are rarely reported, as different studies often choose to report various measures of the task.

Several studies have reported impaired performance of participants with TBI when using the Rey–AVLT (Blachstein, Vakil, & Hoofien, 1993; Zec et al., 2001) or the CVLT (Haut & Shutty, 1992; Novack, Kofoed, & Crosson, 1995). Gardner and Vrbancic (1998) found that the total amount of words acquired in the learning phase (trials 1 to 5 in the CVLT) was the most sensitive measure differentiating between controls and individuals with TBI. Similar results were reported using the Selective Reminding Test (Levin, Grossman, Rose, & Teasdale, 1979; Zec et al., 2001). Unlike verbal learning, visual learning in individuals with TBI is not tested as frequently. Using the Shum Visual Learning Test, Shum et al. (2000) reported that just like

findings concerning verbal information, the learning rate of visual stimuli was slower for individuals with TBI compared to controls. Honan, McDonald, and Fisher (2015) used a computerized version of the Austin Maze task to measure visuospatial learning in individuals with moderate-to-severe TBI. Compared with their control group, they found that TBI patients exhibited significant impairment in this task.

Numerous attempts have been made to detect the underlying impaired processes in individuals with TBI that cause impaired learning rate. Blachstein et al. (1993) proposed that learning rate is composed of two components: the number of words *added* in each learning trial and the number of words *omitted* from trial to trial. Analysis of these two components using the Rey-AVLT on patients with TBI revealed that overall, the patient group had a higher turnover of words from trial to trial, stemming primarily from a higher rate of words omitted. This was interpreted as an inefficient learning strategy, consequently leading to difficulty in transferring information from WM to long-term memory. It could also reflect a greater sensitivity to output interference, which constrains the number of words that can be recalled. This is consistent with a previous study using the Selective Reminding Test. Levin et al. (1979) also reported a higher turnover of words during repeated learning trials for individuals with TBI. Palacios et al. (2013) also reported that individuals with TBI were impaired on all measures of the Rey-AVLT. Based on multiple regression analysis, the researchers concluded that the best predictors of memory impairment were diminution of the left parietal region (because it is associated with verbal memory) and decreases in Fractional Anisotropy (FA). Ariza et al. (2006) showed that impaired verbal memory, measured with the Rey-AVLT, was correlated with left hippocampal head atrophy in individuals with TBI. Ries and Marks (2006) tested

participants following TBI and revealed that not only did they remember less items than controls, they also made more false positive responses and more semantic intrusion errors.

The interaction between encoding and forgetting, tested by delayed recall or recognition, has been investigated in several studies. DeLuca, Schultheis, Madigan, Christodoulou and Averill (2000) found that individuals with TBI required more learning trials than controls to reach a learning criterion of a verbal list. Patients that reached this criterion did not differ from controls on delayed recall and recognition after 30 and 90 minutes. The researchers concluded that the primary deficit of the patients is at the acquisition phase rather than at the retrieval phase. An alternative interpretation could be that patients are less able to resolve output interference at retrieval, and they are only able to do so once the items are well encoded. Wright, Schmitter-Edgecombe and Woo (2010) reached a similar conclusion by analyzing the learning process of the CVLT. They deduced that patients with TBI make poor use of semantic clustering in their learning process, leading to poor encoding and therefore, impaired delayed recall. In their meta-analysis, Allanson, Pestell, Gignac, Yeo, and Weinborn (2017) found that immediate and delayed verbal memory are the best predictors of outcome following TBI. In conclusion, learning rate is impaired following TBI, leading to poor retention over time. Piolino, Desgranges, Manning, North, Jokic, and Eustache (2007) documented a year in the life of patients with TBI before testing the patients' episodic autobiographical memories of that year. It was found that patients' episodic autobiographical memory was impaired compared to controls. This impairment was associated with executive function impairment, indicating frontal lobe involvement in episodic autobiographical memory.

Vakil, Arbell, Gozlan, Hoofien, and Blachstein (1992) tested 40 individuals with moderate-to-severe TBI and 40 controls on the first story from the WMS (Logical memory). Recall of the story was tested immediately, after 40 minutes and after a one-day delay. As predicted, TBI patients recalled less units of information overall and had a steeper forgetting rate over time than the controls. Interestingly, although the control group showed a differential forgetting rate as a function of the importance of the unit of information (determined in a pre-test), the patient group did not demonstrate such a pattern. In other words, while the controls retained the more important information better over time as opposed to the less important information, the forgetting rate of the TBI patients was similar for all types of information. The researchers suggested that the results indicate the patients' difficulty in taking advantage of the differential importance of information. Carlesimo, Sabbadini, Loasses, and Caltagirone (1997) reported similar findings with visual information. Participants with TBI and controls were presented with sets of 16 drawings either semantically related or unrelated. Unlike the controls, the patients with TBI did not utilize the semantic relationships between the drawings to improve their delayed recall. Consistent with these findings, Perri, Carlesimo, Loasses and Caltagirone (2000) reported that patients with TBI did not take advantage of semantic knowledge during word-list memory tests. Another study demonstrated that patients with TBI exhibited reduced semantic clustering in the learning process of a wordlist (CVLT) (Stallings, Boake, & Sherer, 1995).

Episodic memory versus semantic memory: Carlesimo et al. (1998) reported that individuals with TBI had impaired autobiographical memory as well as impaired memory for early-acquired knowledge of public events. Similarly, Roberts, Spitz,

Mundy and Ponsford (2018) reported that patients following severe TBI showed impaired semantic and episodic autobiographical memory when measured at the acute stage, as well as six-months later. Coste, Navarro, Vallat-Azouvi, Brami, Azouvi, and Piolino (2015) tested individuals with TBI on both semantic and episodic memory in addition to administering a neuropsychological test battery. They found that both semantic and episodic memory were impaired for the patients; furthermore, these deficits were associated with a deficit in executive functions.

Contrary to the above studies which reported impairment of both episodic and semantic memory following TBI, the following studies found that TBI affected episodic but not semantic memory. Knight and O'Hagan (2009) tested individuals with TBI on episodic and semantic memory for famous faces. The former requires memory of specific events associated with the famous person, while the latter requires only general knowledge about the person. The results demonstrated that participants with TBI had impaired episodic memory, but intact semantic memory. Similarly, Rasmussen and Berntsen (2014) found that episodic memory was impaired following TBI, although semantic memory remained intact. Interestingly, they also found that impaired episodic memory in individuals with TBI was associated with an impaired ability to imagine future events. This is consistent with literature suggesting that these two processes share a common neuronal network. Similarly, Esopenko and Levine (2017) also showed that individuals with severe TBI had impaired episodic memory, yet intact semantic autobiographical memory; impaired episodic autobiographical memory was associated with diminished cortical volume, particularly in areas linked to the autobiographical network (i.e., parietal, temporal and frontal).

Following the distinctions introduced above between semantic and episodic memory on the one hand, and between semantic memory and semantic processing on the other hand, we could summarize the findings as follows: episodic memory is impaired following TBI, but the impairment is more pronounced when semantic processing or elaboration of the information is required (Carlesimo et al., 1997; Perri et al., 2000; Vakil et al., 1992). Poor semantic processing could be viewed as a reflection of impaired executive functions which are mediated by the frontal lobes (Tranel et al., 1994), which are known to be vulnerable following TBI (Azouvi et al., 2009; Gansler et al., 1996; Draper & Ponsford, 2008). The reports in studies comparing the effect of TBI on episodic and semantic memory are inconsistent. While all of these studies reported impaired episodic memory following TBI, findings on its effect on semantic memory are mixed.

Prospective memory

Prospective memory (PM) refers to "remembering to perform previously planned actions at the right time or within the right time interval or after a certain event takes place while being involved in other activity" (Groot, Wilson, Evans, & Watson, 2002, p. 645). This form of memory can be particularly important for carrying out activities of daily living (Ellis & Kvavilashvili, 2000; Shum, Fleming, & Neulinger, 2002). Individuals with TBI, as well as their relatives, reported that PM is the most challenging memory-related aspect of everyday functioning (Mateer, Sohlberg, & Crinean, 1987). Kvavilashvili and Ellis (1996) distinguish between three types of PM: *time based* (e.g., call a friend at 6 pm), *event based* (e.g., tell my wife when she returns home that a friend called), and *activity based* (e.g., to attach a file after finishing to write the email). The first type is considered to be more difficult as it

requires self-initiation, while the other two are triggered by an external cue. For further discussion of this topic, see the chapter on PM by Verfaellie in this volume.

Shum et al. (2002) identified three common ways to assess PM: questionnaires such as the Prospective Memory Questionnaire (Hannon, Adams, Harrington, Fires-Dias, & Gipson, 1995), psychological tests such as the Memory for Intentions Screening Test – MIST (Raskin, 2009) or the Memory for Intentions Test – MIT (Raskin, Buckheit, & Sherrod, 2010), and experimental procedures in which participants, while continuously performing a task, are asked to do something following a certain amount of time (time based) or when encountering a certain cue (activity based). In their review, Shum, Levin, and Chan (2011) found four studies that used questionnaires on adults with TBI. Hannon et al. (1995) found that self-report on PM measured with the PM Questionnaire weakly correlated with PM performance of individuals on short-term, but not long-term, time and event cued tasks. They concluded that such questionnaires do not necessarily measure PM, but rather memory self-awareness.

Kondo et al. (2010) tested PM using the Rivermead Behavioral Memory Test (Wilson, Cockburn, & Baddeley, 1985) for individuals with DAI. They found an association between impaired PM and measures of white matter (DTI) using FA at voxel level for each participant, in the left para-hippocampal gyrus, left inferior parietal lobe, and left anterior cingulate. Palermo et al. (2018) evaluated PM using the MIST in addition to a battery of tests involving various aspects of executive functions (e.g., Wisconsin Card Sorting Test and Tower of London). As predicted, individuals with TBI had poorer PM. They also found that the updating/WM component of executive functions was associated with both time and event based PM. Raskin,

Buckheit and Waxman (2012) tested individuals with TBI on the Memory for Intentions Test, to evaluate the effect of various aspects of PM measuring tasks, such as length of delay and difficulty of an ongoing task. They found that participants with TBI were impaired on all aspects of the PM measuring tasks. Furthermore, PM performance did not correlate with self-report of PM (Prospective Memory Questionnaire designed by Hannon et al., 1995), but did correlate with measures of executive functions.

Groot et al. (2002) used the Cambridge Behavior Prospective Memory Test to test individuals with TBI. The test includes time and event-based tests of PM. The patient group's performance was significantly poorer than the control group's performance for both tests of PM. Independently, PM performance correlated with retrospective memory and executive function measures. These results are consistent with previous findings, demonstrating that individuals with TBI are impaired on both time and event-based aspects of PM (Carlesimo, Casadio, & Caltagirone, 2004; Shum, Valentine, & Cutmore, 1999). Based on their literature review and meta-analysis, Shum et al. (2011) concluded that patients with sustained TBI have impaired time and event-based PM. In conclusion, findings fairly consistently demonstrate that most aspects of PM are impaired following moderate-to-severe TBI.

Context and source memory

Johnson and Raye (1981) and Schacter, Harbluk, and McLachlan (1984) introduced the distinction between *item* (or target) memory, the information that we intend to remember, versus *source* memory (e.g., temporal order, spatial location), the contextual information that we do not intend to remember. Differing from source memory, which is the explicit memory of context, *context effect* refers to the memory

of context when tested implicitly (therefore this section is not included in the episodic and semantic memory section, which is explicit memory). A context effect is said to occur when memory of target information is improved upon retrieval by the presence of a contextual stimulus (Vakil, Openheim, Falck, Aberbuch, & Groswasser, 1997).

Several functional magnetic resonance imaging (fMRI) studies have demonstrated that various sub-areas within the prefrontal cortex have been associated with source memory (e.g., Dobbins, Simons, & Schacter, 2004). Thus, it is not surprising that patients with TBI often have impaired source memory (Dywan, Segalowitz, Henderson, & Jacoby, 1993). Schmitter-Edgecombe and Seelye (2012) reported that although it remained impaired, source memory measured by temporal order of activities improved one year following TBI. Interestingly, they found that temporal order memory, more than content memory for the activities, was associated with daily memory activity. Contrary to this, the same researchers (Wright, Wong, Obermeit, Woo, Schmitter-Edgecombe, & Fuster, 2014) reported preserved temporal order memory of observed and performed activities. To reconcile their inconsistent findings, the researchers suggested that temporal order memory is preserved under incidental learning instructions assumed to involve more implicit memory processes, but is impaired under intentional instructions.

In a series of studies using a variety of paradigms and contextual information, Vakil and colleagues have consistently shown that although following moderate-to-severe TBI, context memory is impaired when tested explicitly (i.e., source memory), it is in fact preserved when tested implicitly (i.e., context effect) (cf. Vakil, Blachstein, & Hoofien, 1991; re: temporal order judgment; cf. Vakil, Biederman, Liran, Groswasser & Aberbuch,1994, re: frequency judgment; cf. Vakil, Golan,

Grunbaum, Groswasser, & Aberbuch, 1996, re: perceptual background; cf. Vakil et al., 1997, re: modality of presentation; Vakil, Aviv, Mishael, Schwizer Ashkenazi, & Sacher, 2019). In a more recent study, Barak, Vakil and Levy (2013) demonstrated that preserved context effect is expressed during cued and free recall in individuals with TBI. In conclusion, when contextual information (e.g., temporal order, modality) is tested explicitly, i.e., taps source memory, individuals with TBI usually show impaired memory. This is consistent with reports that the frontal lobes are associated with source memory (Dobbins et al., 2004) which are known to be vulnerable following TBI (Avants et al., 2008; Bigler, 2013; Bigler & Maxwell, 2011; Stuss, 2011). Conversely, when memory for contextual information is tested implicitly, a process that does not require effortful retrieval and is thus less dependent on the frontal lobes, such memory is less affected by TBI.

Skill learning

Based on the performance of amnesic patients with medial-temporal lobe lesions, Cohen and Squire (1980) differentiated *declarative* memory (knowing that) from *procedural* memory or skill learning (knowing how). While the former was impaired in amnesics, the latter was preserved, as demonstrated by the ability of the amnesic patients to acquire new motor, perceptual and cognitive skills. Schmitter-Edgecombe and Nissley (2000) showed that for individuals following TBI, skills acquired pre-injury are retained post-injury. Several researchers have attempted to verify whether patients with TBI are able to acquire new skills post-injury. Various studies have shown that individuals with moderate-to-severe TBI have difficulties in implicit sequence learning, as measured with the Serial Reaction Time (SRT) task (Mutter, Howard, & Howard, 1994; Vakil, Kraus, Bor, & Groswasser, 2002, but see

McDowall & Martin, 1996). Vakil, Gordon, Birnstok, Aberbuch, and Groswasser (2001) used the Tower of Hanoi Puzzle (TOHP), a cognitive (problem solving) learning task, for individuals with moderate-to-severe TBI and controls. They found that overall, the TBI group was slower in solving the task compared to controls, and that the controls' learning rate as measured by number of moves to solution was steeper. Vakil and Lev-Ran Galon (2014) measured the baseline level and learning rate of individuals with TBI using two different skill-learning tasks: the TOHP (cognitive task) and the mirror reading task (perceptual task). Consistent with Vakil et al. (2001), the baseline performance of the TOHP was impaired for the TBI group, yet unlike the previous study, the learning rate of the TBI group was comparable to that of controls. Similarly, the TBI group exhibited a poorer baseline and a preserved learning rate with the mirror reading task. There is no suitable explanation accounting for the inconsistent findings regarding the learning rate of the TOHP, aside from the highly varied patient group, as noted by Vakil et al. (2001). Patients with TBI were able to reach automaticity when performing a search-detection task, although at a slower rate than controls (Schmitter-Edgecombe & Beglinger, 2001). This learned skill was retained just as well as controls five and ten months later (Pavawalla & Schmitter-Edgecombe, 2006). Schmitter-Edgecombe and Robertson (2015) tested patients with moderate-to-severe TBI in two phases, post-acute and at eight months post injury, on two versions of the visual search task: a parallel version (bottom-up) which tested pre-attentive visual search abilities, and a serial version (top-down) that tested attentive visual search abilities. The patient group's performance on the pre-attentive visual search was intact for both phases of the task, unlike their performance on the attentive visual search, which was impaired for both phases. The authors

explain these findings based on electrophysiological studies demonstrating the involvement of the parietal lobes in bottom-up visual search, and the frontal lobes in top-down visual search (Li, Gratton, Fabiani, & Knight, 2013). This explains the poor performance of the group following TBI which is known primarily to affect the frontal lobes (Avants et al., 2008; Bigler, 2013; Bigler & Maxwell, 2011; Stuss, 2011). Nissley and Schmitter-Edgecombe (2002) reported that patients with TBI were able to learn at a normal rate, evaluated by an implicit perceptual learning task. In an attempt to reconcile these inconsistent findings, Vakil (2005) proposed that unlike the perceptual tasks, the SRT and TOHP tasks are known to involve the frontal lobes and are thus more challenging for individuals with TBI, since TBI predominantly affects the frontal lobes.

Memory self-awareness

Livengood, Anderson, and Schmitter-Edgecombe (2010) view self-awareness of memory as the "cognitive ability that involves having accurate knowledge of one's memory abilities" (p. 598). While awareness of the impairment could lead to distress and depression (Wilson, 2002), lack of awareness of general deficits, particularly memory deficits, may cause reduced motivation for rehabilitation (Malec & Moessner, 2001). Furthermore, it may lead to unpleasant consequences by setting unrealistic goals (e.g., financial, academic). Several studies have shown that decreased self-awareness or metacognition in TBI is associated with impaired PM (Fleming, Riley, Gill, Gullo, Strong, & Shum, 2008) and executive functions (Bivona et al., 2008). Thus, increasing memory self-awareness should be a primary goal in rehabilitation.

Livengood et al. (2010) differentiated between two methods of evaluation of memory self-awareness following TBI: *offline assessment* and *online assessment*. In the offline assessment method, participants are asked to rate on a questionnaire their everyday memory functioning, and this rating is then compared to the rating of a family member or a rehabilitation staff professional who is familiar with the patient's memory functioning. Some studies have evaluated self-rating by using a standardized questionnaire such as the Everyday Memory Questionnaire (EMQ), and then compared it to actual performance on a standard memory battery. In the online assessment method, typically before carrying out a memory task (e.g., recalling a list of words), participants are asked to estimate and predict their performance on that particular task (e.g., a judgment-of-knowing in which they state how many words they think they will be able to remember). Memory self-awareness is then determined by calculating the gap between performance prediction and actual performance.

Using the offline assessment approach, Oddy, Coughlan, Tyerman, and Jenkins (1985) reported that seven years after onset, only 40% of TBI patients, whose family members reported that they have memory problems, acknowledged such problems. Roche, Fleming, and Shum (2002) used the Comprehensive Assessment of Prospective Memory (CAPM) to test the awareness of participants with TBI of their PM performance compared to their significant others' estimation of their performance. They found that the participants with TBI overestimated their PM performance. Similarly, Sbordone, Seyranian, and Ruff (1998) found that individuals with TBI, regardless of severity of injury, underestimated their cognitive behavioral and emotional difficulties, compared to their significant others' observations. Dirette and Plaisier (2007) interviewed individuals with TBI and their significant others using the

Awareness Questionnaire, and found reduced self-awareness more pronounced in individuals with severe more than in mild TBI. So, unlike the previous study, severity of injury has an effect on self-awareness. The report by Jamora, Young, and Ruff (2012) is inconsistent with the above studies. These researchers tested the relationship between subjective cognitive complaints and objective neuropsychological test results for mild and more severe TBI. They found that patients with mild injuries were more aware and more accurate regarding their complaints about attention deficits, while patients with moderate-to-severe injuries were more accurate in estimating their learning and memory deficits.

Using the online assessment approach, Knight, Harnett, and Titov (2005) tested the accuracy of patients with TBI when predicting their performance on a PM task. Results showed that in addition to impaired PM, patients in predicted their performance more poorly by overestimating their memory, indicating low memory self-awareness. Similarly, O'Brien and Kennedy (2018) used a virtual reality game to assess PM and memory self-awareness in individuals following TBI. In this assessment of memory self-awareness, although patients predicted they would demonstrate low performance, their predictions still overestimated their actual performance.

In contrast to the above studies, Anderson and Schmitter-Edgecombe (2009) tested memory self-awareness on a sample of TBI patients who attended a rehabilitation program. It was found that although patients' memory was consistently impaired compared to that of controls, their estimation of their performance was as accurate as that of controls. Several other studies on patients with TBI reported similar findings; despite impaired memory performance compared to controls, their

estimation of performance was just as accurate as that of controls (Kennedy, 2001;

Schmitter-Edgecombe & Woo, 2004).

Livengood et al. (2010) tested offline and online assessment methods in a

single study using a single sample in order to clarify this pattern of discrepancies

between the two assessment methods. Consistent with their hypothesis, using online

assessment, individuals with TBI were as accurate as controls in their prediction of

memory performance. However, contrary to their hypothesis, these patients were also

accurate in their assessment of memory using offline assessment. The authors raise

the possibility that the fact that participants in their study attended a rehabilitation

program may have contributed to awareness of their memory deficit. Robertson and

Schmitter-Edgecombe (2015) used several measures of self-awareness testing

(metacognitive awareness, anticipatory awareness, error-monitoring and self-

regulation) with a group of participants following moderate-to-severe TBI, at the

acute phase and during recovery, to identify whether self-awareness changes over

time. Their main findings were that error monitoring was impaired and did not

improve over time. They measured error monitoring by using two tasks: the letter

fluency task and five-point task. In the first task participants were asked to provide as

many words (but not nouns) that start with one of three letters (P, R & W), and in the

second task they were asked to produce as many different designs by connecting the

dots. When a participant did not follow instructions, for example producing a noun in

the first tasks or not drawing a straight line in the second task, that was considered as

a monitoring failure error. Furthermore, error monitoring was predictive of

community re-integration. In addition to severity of injury and time since injury,

attendance at a rehabilitation program should also be viewed as a moderator of memory self-awareness, since it may resolve some of the inconsistent findings.

Thus, findings regarding self-awareness when tested offline seem quite consistently impaired following TBI. However, when self-awareness is tested online, the findings are inconsistent. Several studies (Knight et al., 2005; O'Brien & Kennedy, 2018) reported impaired awareness, while other studies did not find such an impairment of self-awareness following TBI (Anderson & Schmitter-Edgecombe (2009); Kennedy, 2001; Schmitter-Edgecombe & Woo, 2004). One possible interpretation of this discrepancy is that the studies reporting impaired self-awareness following TBI used PM as the memory test, while other studies reporting preserved self-awareness used retrospective memory (i.e., list-learning, visual-spatial memory tasks, lists of noun-pairs & story recall). Further research is required in order to understand why it is more difficult for individuals with TBI to estimate their PM than their retrospective memory. A possible explanation for this pattern of more consistent reports of impaired memory self-awareness when tested offline than online, is that the former requires a judgment of a general and abstract situation, while the latter requires a judgment of immediate, specific, concrete questions and performance-dependent feedback, which seems to be easier for individuals with TBI.

Memory remediation

There are two predominant approaches to memory remediation: one is *internal*, encouraging the use of mnemonic strategies such as visual imagery, and the other is *external*, adopting the use of external cues such as electronic cues (e.g., using a smart phone for reminders) or paper and pencil (e.g., keeping a diary) (Cappa,

Benke, Clarke, Rossi, Stemmer, & Van Heugten, 2005; Tsaousides & Gordon, 2009).

The effectiveness of the internal approach has been demonstrated in several studies.

Some studies aimed to improve specific memory processes such as PM using visual

imagery (Potvin, Rouleau, Senechal, & Giguere, 2011) or self-imagination (imagining

from a personal perspective) (Grilli & McFarland, 2011). Self-imagination was found

to be a very effective strategy for improving cued recall (Grilli & Glisky, 2011) and

PM (Potvin et al., 2011). Chiaravalloti, Sandry, Moore, and DeLuca (2016) trained

participants with TBI in 10 sessions over five weeks to improve their learning abilities

by using context and imagery. The researchers reported a significant improvement in

prose learning for the group that participated in the training program. Duval, Coyette,

and Seron (2008) trained TBI participants with three strategies: Dual coding – using

verbal and visual coding, Serial processing – arranging the stimuli (e.g., in alphabetic

order) before processing it further, Speed reduction – emphasis on quality and

accuracy of performance rather than on speed. The goal was to improve three specific

components of the WM central executive: processing load, updating and dual-task

monitoring. They found that this intervention not only improved these WM

components, but also led to recovery that generalized to real life situations. Serino,

Ciaramelli, Santantonio, Malagù, Servadei, and Làdavas (2007) developed a

remediation program targeting the central executive system. The efficiency of the

program was expressed not only in cognitive tasks involving the central executive, but

also generalized to everyday functioning. Mioni, Bertucci, Rosato, Terrett, Rendell,

Zamuner, and Stablum (2017) used the Virtual Week task with the aim of improving

PM performance of individuals with TBI. The task involves a computer-based

program requiring participants to simulate future events. Results showed that although

individuals with TBI had impaired PM, they benefited from this strategy. In addition, patients with TBI showed the advantage of spaced rather than massed practice (Goverover, Arango-Lasprilla, Hillary, Chiaravalloti, & DeLuca, 2009). The generation effect (better memory of self-generated words than words provided) was also demonstrated in individuals with TBI (Goverover, Chiaravalloti, & DeLuca, 2010; Schefft, Dulay, & Fargo, 2008).

Implementation of external strategies has also proven useful as a mnemonic device. Everyday functioning of individuals with TBI was improved by using a notebook or a diary (Ownsworth & McFarland, 1999; Schmitter-Edgecombe, Fahy, Whelan, & Long, 1995). Electronic devices and paging systems were also found to be very helpful for sending reminders of daily activities to TBI patients with memory impairment (Gentry, Wallace, Kvarfordt, & Lynch, 2008; Kirsch, Shenton, & Rowan, 2004). Shum, Fleming, Gill, Gullo, and Strong (2011) have shown that the use of external aids, such as the use of a diary, improved PM.

Fleming, Shum, Strong, and Lightbody (2005) trained individuals following TBI for eight weeks in an attempt to improve their PM. Participants were trained simultaneously with a combination of both internal strategies (i.e., self-awareness with feedback) and external strategies (i.e., the use of a diary or an alarm watch). Training included implementation of these strategies in real life situations. They reported a significant improvement in PM when comparing pre- and post- training performance.

One of the most frequent complaints regarding memory decline is face naming. Manasse, Hux, and Snell (2005) designed an intervention addressing this

problem for participants with TBI. The approach consists of several phases. In the first phase, researchers focus participants' attention on special features of faces in photographs. Participants were instructed to repeat the names loudly and then to read a sentence with imagery association (e.g., for Jim "Imagine Jim working out at the gym"). In the next phase, participants had to implement face naming in real life situations. Researchers reported a significant improvement in face naming compared to the initial baseline. Alashram, Annino, Padua, Romagnoli, and Mercuri (2019) reviewed nine studies that used VR technology for remediation of various TBI impaired cognitive processes. They concluded that 10-20 sessions of 20-40 minutes each can make a significant improvement in memory, executive functions and attention. The VR sessions in the nine reviewed papers included various settings such as a driving simulator, a bike riding simulator, a Caribbean island, a country town, ski runs and a virtual mall. In their literature review on cognitive rehabilitation, Cicerone, Langenbahn, and Braden (2011) concluded that internal strategies are more beneficial for individuals with mild-TBI, while external mnemonics are more beneficial for those with severe-TBI. One of the most challenging aspects of any kind of training is the transfer and generalization of the learned material to real life situations. In a study by Vakil and Heled (2016) using the TOHP, it was demonstrated that the cost of transfer to a new condition was significantly lower under *varied training* (when different versions of a specific task are used for training) than under *constant training* (when the same version of a task is used throughout training). This principle should be implemented in memory remediation techniques together with other cognitive remediation paradigms.

Discussion

TBI results in widespread brain injury, but particularly affects the frontal and temporal lobes (Avants et al., 2008; Bigler, 2013; Bigler & Maxwell, 2011; Stuss, 2011). Additionally, white matter is affected in the form of diffuse axonal injury (Spitz et al., 2013). Unlike localized brain lesions which cause specific impairments (e.g., hippocampal lesion causing amnesia), TBI results in a wide range of cognitive deficits including deficits in attention, speed of processing, executive functions and memory. Even many years after TBI, patients cite memory impairment as their most concerning symptom (Jourdan et al., 2016). The high prevalence of individuals suffering from TBI and the need to characterize their memory deficit, has led to extensive research on the effects of TBI on memory.

When analyzing the effects of TBI on memory we must bear in mind the diffuse nature of these brain injuries and their effect on other cognitive processes which modulate the expression of the memory deficit. For example, the well-documented effect of TBI on executive functions (Draper & Ponsford, 2008; Gansler et al., 1996) has an effect on the encoding and retrieval of information. In Moscovitch's (1994) term "working-with-memory", damage to the frontal lobes (which typically follows TBI) hinders top-down processes such as implementation of strategy, organization, and conceptual elaborative encoding and retrieval.

Literature reviewed in the present chapter illustrates that TBI affects most aspects of human memory function (see Table 1). However, we can ask whether some aspects of memory are more vulnerable than others. In an attempt to address this question, Vakil (2005) suggested that TBI most severely impacts aspects of memory that (1) depend on conceptual processing of items and strategic/effortful elaboration

of those items, and (2) rely on episodic or contextual associations, as in delayed recall tasks. By contrast, those aspects of memory that rely on automatic, implicit and shallow processes are more resistant to impairment in TBI. This assertion is supported by the literature reviewed in the present chapter. Accordingly, there are more consistent reports of an impaired central executive component of WM, which supports effortful processes, than reports concerning impairment of the slave systems (Vallat-Azouvi et al., 2007). Similarly, when analyzing the underlying deficit of the learning process, several researchers attributed TBI learning deficits to poor use of semantic clustering (Wright et al., 2010). This review has also demonstrated that TBI consistently results in impaired semantic organization. When testing the effect of TBI on episodic versus semantic memory, impaired episodic memory was reported more consistently than impaired semantic memory (Knight & O'Hagan, 2009; Rasmussen & Berntsen, 2014). Episodic memory, unlike semantic memory, requires reinstatement of the contextual information to be retrieved (see Chapter X.Y). Findings on source memory versus context effect on memory are also consistent with the pattern described above. Source memory that requires explicit retrieval of incidentally encoded contextual information is consistently found to be impaired following TBI (Dywan et al., 1993). In contrast, context effect which expresses the implicit effect of contextual information on target memory, is consistently found to be preserved following TBI (Vakil et al., 1991, 1994, 1996, 1997). Finally, this pattern is also exhibited in literature on skill learning. Cognitive skills that require a strategic approach (e.g., TOHP) (Vakil et al. 2001) are more frequently found to be affected by TBI compared to perceptual skill learning tasks (Pavawalla & Schmitter-Edgecombe, 2006). These impaired memory aspects are associated with frontal lobe functions;

thus, it is not surprising that such aspects are found to be more susceptible to TBI, which typically involves damage to the frontal lobes.

Memory domain/function	Memory sub-processes	Major findings (vs. controls)
Working Memory	Phonological loop	Preserved
	Visuospatial sketchpad	Preserved
	Central executive	Impaired
Episodic and Semantic Memory	Learning rate (verbal material)	Impaired
	Learning rate (visual material)	Impaired
	Forgetting rate	Preserved (when controlling for learning baseline)
		Impaired
	Episodic autobiographical memory	Mixed results
	Semantic autobiographical memory	
	Implementation of semantic processes (verbal and visual material)	Impaired
Prospective Memory	Time based	Impaired
	Event based	Impaired
Context and Source Memory	Context (implicit measure)	Preserved
	Source (explicit measure)	Impaired

Skill Learning	Perceptual tasks	Preserved (mostly)
	Cognitive tasks	Impaired (mostly)
Memory Self-awareness	Offline test	Impaired
	Online test	Mixed results

Table 1: Summary of studies of memory functioning following TBI

Importantly, some critical aspects of strategy-dependent memory — such as PM, source memory and skill learning — are not usually tested via standard memory batteries. Incorporation of these measures into standard batteries would lead to better patient assessment and the amassing of much needed additional data. Assessment of memory self-awareness is also essential due to its implications for memory remediation as well as rehabilitation in general.

Most of the studies exploring the impact of memory remediation reported a significant effect of training, whether an *internal* or *external* strategy was used. However, transfer or generalization of training to the real world (particularly when an internal training strategy was applied) was not always demonstrated. The implementation of *varied* training may be beneficial in this regard, as demonstrated by Vakil and Heled (2016). Another issue that should be considered when dealing

with memory remediation is that memory deficits following TBI typically do not result from pure deficits, but rather more likely stem from, or are at least modulated by, other cognitive impairments such as executive functions. Accordingly, comprehensive memory remediation should also address such impaired cognitive processes.

Although TBI affects many aspects of memory function, its effect on memory is not uniform and our review highlights numerous dissociations between impaired and preserved memory processes. For example, the dissociation between the central executive and slave systems in WM (Vallat-Azouvi et al., 2007), the dissociation between explicit (source memory) and implicit memory of contextual information (context effect) (Vakil et al., 1991, 1994, 1996, 1997) and the dissociation between episodic and semantic memory (Knight & O'Hagan, 2009). These findings support theoretical models that ascribe different components, mechanisms or systems underlying performance in varied memory tasks. Although no task is process pure, some tasks rely more heavily on some processes than on others, and TBI appears to substantially affect processes involving elaboration of conceptual information and context-dependent encoding and retrieval processes. Thus, the study of TBI can also inform theoretical distinctions brought out through basic-science investigations of human memory surveyed in Volume 1.

In conclusion, research on memory following moderate-to-severe TBI has provided a wealth of data concerning the patterns of impairment seen across a wide range of cognitive tasks (see Figure X). Although our review also highlights some inconsistencies in this literature, these inconsistencies may simply reflect the extreme heterogeneity of the being studied. We see the application of a "systems biology

approach" (Bigler, 2016) to the study of TBI as a particularly fruitful means of integrating neuroimaging and neuropsychological findings. As we learn more about the neural substrates of TBI-related disease we can replace the crude mild-to-severe classification with far more precise taxons. Such improved classification could lead to the development of individualized remediation regimes.

References

Alashram, A. R., Annino, G., Padua, E., Romagnoli, C., & Mercuri, N. B. (2019). Cognitive rehabilitation post traumatic brain injury: A systematic review for emerging use of virtual reality technology. *Journal of Clinical Neuroscience*.

Allanson, F., Pestell, C., Gignac, G. E., Yeo, Y. X., & Weinborn, M. (2017). Neuropsychological predictors of outcome following traumatic brain injury in adults: a meta-analysis. *Neuropsychology Review*, *27*(3), 187-201.

Andelic, N., Sigurdarottir, S., Schanke, A-K., Sandvik, L., Sveen, U., & Roe, C. (2010). Disability, physical health and mental health 1 year after traumatic brain injury. *Disability and Rehabilitation*, *32,* 1122-1131.

Anderson, J. W., & Schmitter-Edgecombe, M. (2009). Predictions of episodic memory following moderate to severe traumatic brain injury during inpatient rehabilitation. *Journal of Clinical and Experimental Neuropsychology*, *31*(4), 425-438.

Anderson, T. M., & Knight, R. G. (2010). The long-term effects of traumatic brain injury on the coordinative function of the central executive. *Journal of Clinical and Experimental Neuropsychology*, *32*(10), 1074-1082.

Ariza, M., Serra-Grabulosa, J. M., Junqué, C., Ramírez, B., Mataró, M., Poca, A., Bargall´o, N., & Sahuquillo, J. (2006). Hippocampal head atrophy after traumatic brain injury. *Neuropsychologia*, *44*(10), 1956-1961.

Asloun, S., Soury, S., Couillet, J., Giroire, J. M., Joseph, P. A., Mazaux, J. M., & Azouvi, P. (2008). Interactions between divided attention and working-

memory load in patients with severe traumatic brain injury. *Journal of Clinical and Experimental Neuropsychology*, *30*(4), 481-490.

Avants, B., Duda, J.T., Kim, J., Zhang, H., Pluta, J., Gee, J. C., & Whyte, J. (2008). Multivariate analysis of structural and diffusion imaging in traumatic brain injury. *Academic Radiology*, *15*, 1360-1375.

Axelrod, B. N., Fichtenberg, N. L., Liethen, P. C., Czarnota, M. A., & Stucky, K. (2001). Performance characteristics of postacute traumatic brain injury patients on the WAIS-III and WMS-III. *Clinical Neuropsychology*, *15*, 516–520.

Azouvi, P., Arnould, A., Dromer, E., & Vallat-Azouvi, C. (2017). Neuropsychology of traumatic brain injury: an expert overview. *Revue Neurologique*, *173*(7-8), 461-472.

Azouvi, P., Jokic, C., Van der Linden, M., Marlier, N., & Russel, B. (1996). Working memory and supervisory control after severe closed-head injury: A study of dual task performance and random generation. *Journal of Clinical and Experimental Neuropsychology*, *18*, 317-337.

Azouvi, P, & Vallat-Azouvi, C., & Belmont, A. (2009). Cognitive deficits after traumatic coma. *Progress in Brain Research,* 177. 89-110.

Baddeley, A. (2003). Working memory: Looking back and looking forward. *Nature Review Neuroscience, 4,* 829-839.

Barak, O., Vakil, E., & Levy, D.A. (2013). Environmental context effects on episodic memory are dependent on retrieval mode and modulated by

neuropsychological status. *Quarterly Journal of Experimental Psychology,* 66, 2008-2022.

Bigler, E. D. (2013). Traumatic brain injury, neuroimaging, and neurodegeneration. *Frontiers in Human Neuroscience*, *7*, 395-395.

Bigler, E. D. (2016). Systems biology, neuroimaging, neuropsychology, neuroconnectivity and traumatic brain injury. *Frontiers in Systems Neuroscience, 10*, 55.

Bigler, E. D., Johnson, S. C., Anderson, C. V., & Blatter, D. D. (1996). Traumatic brain injury and memory: The role of hippocampal atrophy. *Neuropsychology, 10,* 333-342.

Bigler, E. D., & Maxwell, W. L. (2011). Neuroimaging and neuropathology of TBI. *NeuroRehabilitation*, *28*(2), 63-74.

Bivona, U., Ciurli, P., Barba, C., Onder, G., Azicnuda, E., Silvestro, D., ... & Formisano, R. (2008). Executive function and metacognitive self-awareness after severe traumatic brain injury. *Journal of the International Neuropsychological Society*, *14*(5), 862-868.

Blachstein, H., Vakil, E., & Hoofien, D. (1993). Impaired learning in patients with closed-head injuries: An analysis of components of the acquisition process. *Neuropsychology*, *7*, 530–535.

Bramlett, H.M., & Dietrich, W.D. (2015). Long-term consequences of traumatic brain injury: Current status of potential mechanisms of injury and neurological outcomes. *Journal of Neurotrauma*, *32*, 1834-1848.

Buschke, H., & Fuld, P. A. (1974). Evaluation of storage, retention, and retrieval in disordered memory and learning. *Neurology*, *24*, 1019-1025.

Caeyenberghs, K., Verhelst, H., Clemente, A., & Wilson, P.H. (2017). Mapping the functional connectome in traumatic brain injury: What can graph metrics tell us? *NeuroImage, 160*, 113-123

Canty, A. L., Shum, D. H., Levin, H. S., & Chan, R. C. (2014). Memory impairments after traumatic brain injury. *Understanding Traumatic Brain Injury: Current Research and Future Directions*, 71. In Levin, H., Shum, D., & Chan, R. (Eds.). (2014). *Understanding Traumatic Brain Injury: Current Research and Future Directions*. Oxford University Press.

Cappa, S. F., Benke, T., Clarke, S., Rossi, B., Stemmer, B., & Van Heugten, C. M. (2005). EFNS guidelines on cognitive rehabilitation: Report of an EFNS task force. *European Journal of Neurology, 12,* 665-680.

Carlesimo, G. A., Casadio, P., & Caltagirone, C. (2004). Prospective and retrospective components in the memory for actions to be performed in patients with severe closed-head injury. *Journal of the International Neuropsychological Society*, *10*(5), 679-688.

Carlesimo, G. A., Sabbadini, M., Bombardi, P., Di Porto, E., Loasses, A., & Caltagirone, C. (1998). Retrograde memory deficits in severe closed head injury patients. *Cortex, 34,* 1-23.

Carlesimo, G. A., Sabbadini, M., Loasses, A., & Caltagirone, C. (1997). Forgetting

from long-term memory in severe closed-head injury patients: Effect of

retrieval conditions and semantic organization. *Cortex, 33,* 131-142.

Chiaravalloti, N. D., Sandry, J., Moore, N. B., & DeLuca, J. (2016). An RCT to treat

learning impairment in traumatic brain injury: the TBI-MEM

trial. *Neurorehabilitation and Neural Repair*, *30*(6), 539-550.

Christodoulou, C., DeLuca, J., Ricker, J. H., Madigan, N. K., Bly, B. M., Lange, G.,

Kalnin, A. J., Liu, W. C., Steffener, J., Diamond, B. J., & Ni, A. C. (2001).

Functional magnetic resonance imaging of working memory impairment after

traumatic brain injury. *Journal of Neurology, Neurosurgery and Psychiatry,

71,* 161-168.

Cicerone, K. D., Langenbahn, D. M., & Braden, C. (2011). Evidence-based cognitive

rehabilitation: Updated review of the literature from 2003 through 2008.

Archives of Physical Medicine and Rehabilitation, 92, 519-530.

Cohen, N. J., & Squire, L. R. (1980). Preserved learning and retention of pattern-

analyzing skill in amnesia: Dissociation of knowing how and knowing that.

Science, *210*, 207-210.

Corriveau-Lecavalier, N., Ouellet, É., Boller, B., & Belleville, S. (2018). Use of

immersive virtual reality to assess episodic memory: A validation study in

older adults. *Neuropsychological Rehabilitation*, 1-19.

Coste, C., Navarro, B., Vallat-Azouvi, C., Brami, M., Azouvi, P., & Piolino, P. (2015). Disruption of temporally extended self-memory system following traumatic brain injury. *Neuropsychologia*, *71*, 133-145.

Delis, D. C., Kramer, J. H., Kaplan, E., & Ober, B. A. (1987). *California Verbal Learning Test: Research edition*. San Antonio, TX: The Psychological Corporation.

DeLuca, J., Schultheis, M. T., Madigan, N. K., Christodoulou, C., & Averill, A. (2000). Acquisition versus retrieval deficits in traumatic brain injury: Implications for memory rehabilitation. *Archives of Physical and Medical Rehabilitation*, *81*, 1327-1333.

Dewan, M. C., Rattani, A., Gupta, S., Baticulon, R. E., Hung, Y. C., Punchak, M., ... & Rosenfeld, J. V. (2018). Estimating the global incidence of traumatic brain injury. *Journal of Neurosurgery*, *1*(aop), 1-18.

Dirette, D. K., & Plaisier, B. R. (2007). The development of self-awareness of deficits from 1 week to 1 year after traumatic brain injury: Preliminary findings. *Brain Injury*, *21*(11), 1131-1136.

Dobbins, I.G., Simons, J.S., & Schacter, D.L., (2004). fMRI evidence for separable and lateralized prefrontal memory monitoring processes. *Journal of Cognitive Neuroscience* 16(6), 908-920.

Dockree, P. M., Kelly, S. P., Roche, R. A., Hogan, M. J., Reilly, R. B., & Robertson, I. H. (2004). Behavioural and physiological impairments of sustained attention after traumatic brain injury. *Cognitive Brain Research*, *20*(3), 403-414.

Draper, K., & Ponsford, J. (2008). Cognitive functioning ten years following traumatic brain injury and rehabilitation. *Neuropsychology*, *22*(5), 618-625.

Dunning, D. L., Westgate, B., & Adlam, A. L. (2016). A meta-analysis of working memory impairments in survivors of moderate-to-severe traumatic brain injury. *Neuropsychology, 30*(7), 811-819.

Duval, J., Coyette, F., & Seron, X. (2008). Rehabilitation of the central executive component of working memory: a re-organisation approach applied to a single case. *Neuropsychological Rehabilitation*, *18*(4), 430-460.

Dywan, J, Segalowitz, S. J., Henderson, D., & Jacoby, L. (1993). Memory for source after traumatic brain injury. *Brain and Cognition*, *21*, 20-43.

Ellis, J. & Kvavilashvili, L. (2000). Prospective memory in 2000: Past, present, and future directions*. Applied Cognitive Psychology, 14,* 1-9.

Esopenko, C., & Levine, B. (2017). Autobiographical memory and structural brain changes in chronic phase TBI. *Cortex*, *89*, 1-10.

Felmingham, K. L., Baguley, I. J., & Green, A. M. (2004). Effects of diffuse axonal injury on speed of information processing following severe traumatic brain injury. *Neuropsychology*, *18*(3), 564-571.

Ferraro, F. R. (1996). Cognitive slowing in closed-head injury. *Brain and Cognition*, *32*, 429-440.

Fisher, D. C., Ledbetter, M. F., Cohen, N. J., Marmor, D., & Tulsky, D. S. (2000). WAIS-III and WMSIII profiles of mildly to severely brain-injured patients. *Applied Neuropsychology*, *7*, 126-132.

Fleming, J., Riley, L., Gill, H., Gullo, M. J., Strong, J., & Shum, D. (2008). Predictors of prospective memory in adults with traumatic brain injury. *Journal of the International Neuropsychological Society*, *14*(5), 823-831.

Fleming, J. M., Shum, D., Strong, J., & Lightbody, S. (2005). Prospective memory rehabilitation for adults with traumatic brain injury: A compensatory training program. *Brain Injury, 19,* 1-10.

Gansler, D. A., Covall, S., McGrath, N., & Oscar-Berman, M. (1996). Measures of prefrontal dysfunction after closed head injury. *Brain and Cognition*, *30*(2), 194-204.

Gardner, S. D., & Vrbancic, M. I. (1998). Which California Verbal Learning Test factors discriminate moderate and severe head injury from normals? *Brain and Cognition*, *37*, 10-13.

Gentry, T., Wallace, J., Kvarfordt, C., & Lynch, K. B. (2008). Personal digital assistants as cognitive aids for individuals with severe traumatic brain injury: A community-based trial. *Brain Injury, 22,* 19-24.

Goldstein, F. C., & Levin, H. S. (1995). Neurobehavioral outcome of traumatic brain injury in older adults: Initial findings. *Journal of Head Trauma Rehabilitation*, *10*, 57-73.

Goverover, Y., Arango-Lasprilla, J. C., Hillary, F. G., Chiaravalloti, N., & DeLuca, J. (2009). Application of the spacing effect to improve learning and memory for functional tasks in traumatic brain injury: A pilot study. *American Journal of Occupational Therapy, 63,* 543-548.

Goverover, Y., Chiaravalloti, N., & DeLuca, J. (2010). Pilot study to examine the use of self-generation to improve learning and memory in people with traumatic brain injury. *American Journal of Occupational Therapy*, *64*(4), 540-546.

Grilli, M. D. & Glisky, E. L. (2011). The self-imagination effect: Benefits of a self-referential encoding strategy on cued recall in memory-impaired individuals with neurological damage. *Journal of the International Neuropsychological Society, 17,* 929-933.

Grilli, M. D. & McFarland, C. P. (2011). Imagine that: Self-imagination improves prospective memory in memory-impaired individuals with neurological damage. *Neuropsychological Rehabilitation, 21,* 847-859.

Groot, Y. C. T., Wilson, B. A., Evans, J., & Watson, P. (2002). Prospective memory functioning in people with and without brain injury. *Journal of the International Neuropsychological Society, 8,* 645-654.

Hannon, R., Adams, P., Harrington, S., Fires-Dias, C., & Gipson, M. (1995). Effects of

brain injury and age on prospective memory self-rating and performance.

Rehabilitation Psychology, 40, 289-298.

Haut, M. W., & Shutty, M. S. (1992). Patterns of verbal learning after closed head

injury. *Neuropsychology*, *6*, 51-58.

Honan, C. A., McDonald, S., & Fisher, A. (2015). Visuospatial learning in traumatic

brain injury: An examination of impairments using the computerised Austin

Maze Task. *Brain Impairment*, *16*(1), 19-27.

Hunter, J. V., Wilde, E. A., Tong, K. A., & Holshouser, B. A. (2012). Emerging imaging

tools for use with traumatic brain injury research. *Journal of

Neurotrauma, 29*, 654-671.

Jamora, C. W., Young, A., & Ruff, R. M. (2012). Comparison of subjective cognitive

complaints with neuropsychological tests in individuals with mild vs more

severe traumatic brain injuries. *Brain Injury, 26,* 36-47.

Johnson, M. K., & Raye, C. L. (1981). Reality monitoring. *Psychological review*, *88*, 67-

85.

Johnson, V. E., Stewart, W., & Smith, D. H. (2013). Axonal pathology in traumatic

brain injury. *Experimental Neurology, 246,* 35-43.

Jourdan, C., Bayen, E., Pradat-Diehl, P., Ghout, I., Darnoux, E., Azerad, S., ... & Azouvi,

P. (2016). A comprehensive picture of 4-year outcome of severe brain

injuries. Results from the PariS-TBI study. *Annals of physical and rehabilitation medicine*, *59*(2), 100-106.

Kasahara, M., Menon, D. K., Salmond, C. H., Outtrim, J. G., Tavares, J. V., Carpenter, T. A., Pickard, J. D., Sahakian, B. J., & Stamatakis, E. A. (2011). Traumatic brain injury alters the functional brain network mediating working memory. *Brain Injury, 5,* 1170-1187.

Kennedy, M. R. (2001). Retrospective confidence judgements made by adults with traumatic brain injury: Relative and absolute accuracy. *Brain Injury*, *15*(6), 469-487.

Kirsch, N. L., Shenton, M., & Rowan, J. (2004). A generic, 'in-house', alphanumeric paging system for prospective activity impairments after traumatic brain injury. *Brain Injury, 18,* 725-734.

Knight, R. J., Harnett, M., & Titov, N. (2005). The effects of traumatic brain injury on the predicted and actual performance of a test of prospective remembering. *Brain Injury, 19,* 19-27.

Knight, R. J. & O'Hagan, K. (2009). Autobiographical memory in long-term survivors of severe traumatic brain injury. *Journal of Clinical and Experimental Neuropsychology, 31,* 575-583.

Kondo, K., Maruishi, M., Ueno, H., Sawada, K., Hashimoto, Y., Ohshita, T., Takahashi, T., Ohtsuki, T., & Matsumoto, M. (2010). The pathophysiology of prospective

memory failure after diffuse axonal injury-Lesion-symptom analysis using

diffusion tensor imaging. *BMC Neuroscience*, *11*(1), 147.

Kvavilashvili, L., & Ellis, J. (1996). Varieties of intention: Some distinctions and

classifications. *Prospective memory: Theory and applications*, *6*, 183-207.

Leclercq, M., Couillet, J., Azouvi, P., Marlier, N., Martin, Y., Strypstein, E., &

Rousseaux, M. (2000). Dual task performance after severe diffuse traumatic

brain injury or vascular prefrontal damage. *Journal of Clinical and

Experimental Neuropsychology*, *22*, 339-350.

Levin, H. S., Grossman, R. G., Rose, J. E., & Teasdale, G. (1979). Long-term

neuropsychological outcome of closed head injury. *Journal of Neurosurgery*,

50, 412-422.

Levine, B., Kovacevic, N., Nica, E. I., Schwartz, M. L., Gao, F., & Black, S. E. (2013).

Quantified MRI and cognition in TBI with diffuse and focal

damage. *NeuroImage: Clinical*, *2*, 534-541.

Li, L., Gratton, C., Fabiani, M., & Knight, R. T. (2013). Age-related frontoparietal

changes during the control of bottom-up and top-down attention: an ERP

study. *Neurobiology of Aging*, *34*, 477-488.

Livengood, M., Anderson, J. W., & Schmitter-Edgecombe M. (2010). Assessment of

memory self-awareness following traumatic brain injury. *Brain Injury, 24,*

598-608.

Madigan, N. K., DeLuca, J., Diamond, B. J., Tramontano, G., & Averill, A. (2000).

Speed of information processing in traumatic brain injury: Modality-specific

factors. *Journal of Head Trauma Rehabilitation*, *15*, 943-956.

Malec, J. F. & Moessner, A. M. (2001). Self-awareness, distress, and post acute

rehabilitation outcome. *Rehabilitation Psychology, 45,* 227-241.

Manasse, N. J., Hux, K., & Snell, J. (2005). Teaching face–name associations to

survivors of traumatic brain injury: A sequential treatment approach. *Brain

Injury, 19,* 633-641.

Mangels, J., Craik, F., Levine, B., Schwartz, M., & Stuss, D. (2000). Chronic deficits in

item and context memory following traumatic brain injury: A function of

attention and injury severity. *Brain and Cognition*, *44*, 107-112.

Mateer, C. A., Sohlberg, M. M., & Crinean, J. (1987). Focus on clinical research:

Perceptions of memory function in individuals with closed-head injury. *The

Journal of Head Trauma Rehabilitation,* 2*(*3), 74-84.

Mathias, J. L., & Wheaton, P. (2007). Changes in attention and information-

processing speed following severe traumatic brain injury: a meta-analytic

review. *Neuropsychology*, *21*(2), 212 -223.

McDowall, J., & Martin, S. (1996). Implicit learning in closed head injured subjects:

Evidence from an event sequence learning task. *New Zealand Journal of

Psychology, 25*(1), 2-6.

McKee, A. C., & Daneshvar, D. H. (2015). The neuropathology of traumatic brain

injury. In *Handbook of Clinical Neurology* (Vol. 127, pp. 45-66). Elsevier.

Merzagora, A. C. R., Izzetoglu, M., Onaral, B., & Schultheis, M. T. (2014). Verbal working memory impairments following traumatic brain injury: an fNIRS investigation. *Brain Imaging and Behavior*, *8*(3), 446-459.

Mioni, G., Bertucci, E., Rosato, A., Terrett, G., Rendell, P. G., Zamuner, M., & Stablum, F. (2017). Improving prospective memory performance with future event simulation in traumatic brain injury patients. *British Journal of Clinical Psychology*, *56*(2), 130-148.

Moscovitch, M. (1994). Memory and working with memory: Evaluation of a component process model and comparisons with other models. In D. L, Schacter, & E, Tulving (Eds.), *Memory systems 1994*. Cambridge: MIT Press.

Mutter, S. A., Howard, J. H., & Howard, D. V. (1994). Serial pattern learning after head injury. *Journal of Clinical and Experimental Neuropsychology*, *16*, 271-288.

Nash, S., Luauté, J., Bar, J. Y., Sancho, P. O., Hours, M., Chossegros, L., ... & Boisson, D. (2014). Cognitive and behavioural post-traumatic impairments: what is the specificity of a brain injury? A study within the ESPARR cohort. *Annals of Physical and Rehabilitation Medicine*, *57*(9-10), 600-617.

Nissley, H. M., & Schmitter-Edgecombe, M. (2002). Perceptually based implicit learning in severe closed-head injury patients. *Neuropsychology*, *16*, 111-122.

Novack, T. A., Kofoed, B. A., & Crosson, B. (1995). Sequential performance on the California Verbal Learning Test following traumatic brain injury. *Clinical Neuropsychologist*, *9*, 38-43.

O'Brien, K. H., & Kennedy, M. R. (2018). Predicting Remembering: Judgments of Prospective Memory After Traumatic Brain Injury. *Journal of Speech, Language, and Hearing Research*, *61*(6), 1393-1408.

Oddy, M., Coughlan, T., Tyerman, A., & Jenkins, D. (1985). Social adjustment after closed head injury: A further follow-up seven years after injury. *Journal of Neurology, Neurosurgery and Psychiatry, 48,* 564-568.

Ownsworth, T. L. & McFarland, K. (1999). Memory remediation in long-term acquired brain injury: Two approaches in diary training. *Brain Injury, 13,* 605-626.

Palacios, E. M., Fernandez-Espejo, D., Junque, C., Sanchez-Carrion, R., Roig, T., Tormos, J. M., Bargallo, N., & Vendrell, P. (2011). Diffusion tensor imaging differences relate to memory deficits in diffuse traumatic brain injury. *BMC Neurology*, *11*(1), 24.

Palacios, E. M., Sala-Llonch, R., Junque, C., Fernandez-Espejo, D., Roig, T., Tormos, J. M., Bargallo, N., & Vendrell, P. (2013). Long-term declarative memory deficits in diffuse TBI: correlations with cortical thickness, white matter integrity and hippocampal volume. *Cortex*, *49*(3), 646-657.

Palermo, L., Cinelli, M.C., Piccardi, L., De Felice, S., Ciurli, P., Incoccia, C., Zompanti, L. & Guariglia, C. (2018). Cognitive functions underlying prospective memory deficits: A study on traumatic brain injury. *Applied Neuropsychology: Adult*, 1-15.

Pavawalla, S. P., & Schmitter-Edgecombe, M. (2006). Long-term retention of skilled visual search following severe traumatic brain injury. *Journal of the International Neuropsychological Society*, *12*(6), 802-811.

Perri, R., Carlesimo, G. A., Loasses, A., & Caltagirone, C. (2000). Deficient intentional access to semantic knowledge in patients with severe closed-head injury. *Cortex*, *36*, 213-225.

Piolino, P., Desgranges, B., Manning, L., North, P., Jokic, C., & Eustache, F. (2007). Autobiographical memory, the sense of recollection and executive functions after severe traumatic brain injury. *Cortex*, *43*(2), 176-195.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience*, *13*, 25-42.

Potvin, M. J., Rouleau, I., Senechal, G., & Giguere, J. F. (2011). Prospective memory rehabilitation based on visual imagery techniques. *Neuropsychological Rehabilitation, 21,* 899-924.

Raskin, S. A. (2009). Memory for intentions screening test: Psychometric properties and clinical evidence. *Brain Impairment*, *10*(1), 23-33.

Raskin, S. A., Buckheit, C. A., & Sherrod, C. (2010). Memory for Intentions Test. Lutz, FL: Psychological Assessment Resources, Inc.

Raskin, S. A., Buckheit, C. A., & Waxman, A. (2012). Effect of type of cue, type of response, time delay and two different ongoing tasks on prospective memory functioning after acquired brain injury. *Neuropsychological Rehabilitation*, *22*(1), 40-64.

Rasmussen, K. W., & Berntsen, D. (2014). Autobiographical memory and episodic future thinking after moderate to severe traumatic brain injury. *Journal of Neuropsychology*, *8*(1), 34-52.

Ries, M., & Marks, W. (2006). Heightened false memory: A long-term sequela of severe closed head injury. *Neuropsychologia*, *44*(12), 2233-2240.

Roberts, C. M., Spitz, G., Mundy, M., & Ponsford, J. L. (2018). Retrograde Autobiographical Memory from PTA emergence to six-month follow-up in moderate to severe Traumatic Brain Injury. *The Journal of Neuropsychiatry and Clinical Neurosciences*, 1-11.

Robertson, K., & Schmitter-Edgecombe, M. (2015). Self-awareness and traumatic brain injury outcome. *Brain Injury*, *29*(7-8), 848-858.

Roche, N. L., Fleming, J. M., & Shum, D. H. (2002). Self-awareness of prospective memory failure in adults with traumatic brain injury. *Brain Injury*, *16*(11), 931-945.

Sanchez-Carrion, R., Fernandez-Espejo, D., Junque, C., Falcon, C., Bargallo, N., Roig, T., ... & Vendrell, P. (2008). A longitudinal fMRI study of working memory in severe TBI patients with diffuse axonal injury. *Neuroimage*, *43*(3), 421-429.

Sbordone, R. J., Seyranian, G. D., & Ruff, R. M. (1998). Are the subjective complaints of traumatically brain injured patients reliable?. *Brain Injury*, *12*(6), 505-515.

Schacter, D. L., Harbluk, J. L., & McLachlan, D. R. (1984). Retrieval without recollection: An experimental analysis of source amnesia. *Journal of Verbal Learning & Verbal Behavior, 23,* 593-611.

Schefft, B. K., Dulay, M. F., & Fargo, J. D. (2008). The use of a self-generation memory encoding strategy to improve verbal memory and learning in patients with traumatic brain injury. *Applied Neuropsychology, 15,* 61-68.

Schmitter-Edgecombe, M. & Beglinger, L. (2001). Acquisition of skilled visual search performance following severe closed-head injury. *Journal of the International Neuropsychological Society, 7,* 615-630.

Schmitter-Edgecombe, M., Fahy, J., Whelan, J., & Long, C. (1995). Memory remediation after severe closed head injury. Notebook training versus supportive therapy. *Journal of Consulting and Clinical Psychology, 63,* 484-489.

Schmitter-Edgecombe, M., & Kibby, M. K. (1998). Visual selective attention after severe closed head injury. *Journal of the International Neuropsychological Society*, *4*, 144-159.

Schmitter-Edgecombe, M. & Nissley, H. M. (2000). Effects of divided attention on automatic and controlled components of memory after severe closed-head injury. *Neuropsychology, 14,* 559-569.

Schmitter-Edgecombe, M., & Robertson, K. (2015). Recovery of visual search following moderate to severe traumatic brain injury. *Journal of Clinical and Experimental Neuropsychology*, *37*(2), 162-177.

Schmitter-Edgecombe, M., & Seelye, A. M. (2012). Recovery of content and temporal order memory for performed activities following moderate to severe traumatic brain injury. *Journal of Clinical and Experimental Neuropsychology*, *34*(3), 256-268.

Schmitter-Edgecombe, M., & Woo, E. (2004). Memory self-awareness and memory self-monitoring following severe closed-head injury. *Brain Injury*, *18*(10), 997-1016.

Schretlen, D. J., & Shapiro, A. M. (2003). A quantitative review of the effects of traumatic brain injury on cognitive functioning. *International Review of Psychiatry*, *15*(4), 341-349.

Serino, A., Ciaramelli, E., Santantonio, A. D., Malagù, S., Servadei, F., & Làdavas, E. (2007). A pilot study for rehabilitation of central executive deficits after traumatic brain injury. *Brain Injury*, *21*(1), 11-19.

Shum, D., Fleming, J., Gill, H., Gullo, M. J., & Strong, J. (2011). A randomized controlled trial of prospective memory rehabilitation in adults with traumatic brain injury. *Journal of Rehabilitation Medicine*, *43*(3), 216-223.

Shum, D., Fleming, J., & Neulinger, K. (2002). Prospective memory and traumatic brain injury: A review. *Brain Impairment*, *3*(1), 1-16.

Shum, D., Levin, H., & Chan, R. C. (2011). Prospective memory in patients with closed head injury: A review. *Neuropsychologia*, *49*(8), 2156-2165.

Shum, D., Valentine, M., & Cutmore, T. (1999). Performance of individuals with severe long-term traumatic brain injury on time-, event-, and activity-based prospective memory tasks. *Journal of Clinical and Experimental Neuropsychology*, *21*, 49-58.

Shum, D. H. K., Harris, D., & O'Gorman, J. G. (2000). Effects of severe traumatic brain injury on visual memory. *Journal of Clinical and Experimental Neuropsychology*, *22*, 25-39.

Slovarp, L., Azuma, T., & LaPointe, L. (2012). The effect of traumatic brain injury on sustained attention and working memory. *Brain injury*, *26*(1), 48-57.

Spitz, G., Maller, J. J., O'Sullivan, R., & Ponsford, J. L. (2013). White matter integrity following traumatic brain injury: the association with severity of injury and cognitive functioning. *Brain Topography*, *26*(4), 648-660.

Stallings, G. A., Boake, C., & Sherer, M. (1995). Comparison of the California Verbal

Learning Test and the Rey Auditory Verbal Learning Test in head-injured

patients. *Journal of Clinical and Experimental Neuropsychology*, *17*, 706-712.

Stuss, D. T. (2011). Traumatic brain injury: relation to executive dysfunction and the

frontal lobes. *Current Opinion in Neurology*, *24*, 584-589.

Taylor, C.A., Bell, J.M., Breiding, M.J., & Xu, L. (2017). Traumatic brain injury–related

emergency department visits, hospitalizations, and deaths — United States,

2007 and 2013. *Surveillance Summaries, 66(9)*, 1-16. Atlanta, Georgia:

Centers for Disease Control and Prevention, National Center for Injury

Prevention and Control.

Tranel, D., Anderson, S.W., & Benton. A (1994). Development of the concept of

'executive functioning' and its relation to the frontal lobes. In F. Boller & J.

Grafman (Eds.), *Handbook of Neuropsychology* (vol. 9., pp. 125-148.)

Amsterdam: Elsevier.

Tsaousides, T. & Gordon, W. A. (2009). Cognitive rehabilitation following traumatic

brain injury: Assessment to treatment. *Mount Sinai Journal of Medicine, 76,*

173-181.

Tulving, E. (1972). Episodic and semantic memory. *Organization of memory*, *1*, 381-

403.

Vakil, E. (2005). The Effect of moderate to severe traumatic brain injury (TBI) on different aspects of memory: A selective review. *Journal of Clinical and Experimental Neuropsychology, 27,* 977-1021.

Vakil, E. (2012). Neuropsychological assessment: Principles, rationale, and challenges. *Journal of Clinical and Experimental Neuropsychology, 34,* 135-150.

Vakil, E. (2013). Breakdowns in everyday memory functioning following moderate-to-severe Traumatic Brain Injury (TBI). In T. Perfect & S. Lindsay (Eds.), *Handbook of Applied Memory* (pp. 201-217). CA, USA: Sage Publications.

Vakil, E., Arbell, N., Gozlan, M., Hoofien, D., & Blachstein, H. (1992). Relative importance of informational units and their role in long-term recall by closed-head-injured patients and control groups. *Journal of Consulting and Clinical Psychology, 60,* 802-803.

Vakil, E., Aviv, O., Mishael, M., Schwizer Ashkenazi, S., & Sacher, Y. (2019). Direct and indirect measures of context in patients with mild-to-severe traumatic brain injury (TBI): The additive contribution of eye tracking. *Journal of Clinical and Experimental Neuropsychology*, 1-9.

Vakil, E., Biederman, Y., Liran, G., Groswasser, Z., & Aberbuch, S. (1994). Head injured patients and control group: Implicit vs. explicit measures of frequency judgment. *Journal of Clinical and Experimental Neuropsychology*, *16*, 539-546.

Vakil, E., & Blachstein, H. (1997). Rey AVLT: Developmental norms for adults and the

    sensitivity of different measures to age. *The Clinical Neuropsychologist*, *11*,

    356-369.

Vakil, E., Blachstein, H., & Hoofien, D. (1991). Automatic temporal order judgment:

    The effect of intentionality of retrieval on closed-head-injured patients.

    Journal of Clinical and Experimental Neuropsychology, *13*, 291-298.

Vakil, E., Greenstein, Y., Blachstein, H. (2010). Normative Data for Composite Scores

    for Children and Adults Derived from the Rey Auditory Verbal Learning Test.

    The Clinical Neuropsychologist, 24, 662-677.

Vakil, E., Golan, H., Grunbaum, E., Groswasser, Z., & Aberbuch, S. (1996). Direct and

    indirect measures of contextual information in brain-injured patients.

    Neuropsychiatry, Neuropsychology, and Behavioral Neurology, *9*, 176-181.

Vakil, E., Gordon, Y., Birnstok, S., Aberbuch, S., & Groswasser, Z. (2001). Declarative

    and nondeclarative sequence learning tasks: Closed-head injured patients

    versus control participants. *Journal of Clinical and Experimental*

    Neuropsychology, 23, 207-214.

Vakil, E., & Heled, E. (2016). The effect of constant versus varied training on transfer

    in a cognitive skill learning task: The case of the Tower of Hanoi

    Puzzle. *Learning and Individual Differences*, *47*, 207-214.

Vakil, E., Kraus, A., Bor, B., & Groswasser, Z. (2002). Impaired skill learning in patients with severe closed-head injuries as demonstrated by the serial reaction time (SRT) task. *Brain and Cognition, 50* 304-315.

Vakil, E., & Lev-Ran Galon, C. (2014). Baseline performance and learning rate of conceptual and perceptual skill-learning tasks: the effect of moderate to severe traumatic brain injury. *Journal of Clinical and Experimental Neuropsychology*, *36*(5), 447-454.

Vakil, E., Openheim, M., Falck, D., Aberbuch, S., & Groswasser, Z. (1997). The indirect influence of modality on the direct memory for words and their modality: Closed-head injured patients versus control participants. *Neuropsychology*, *11*, 545-551.

Vallat-Azouvi, C., Weber, T., Legrand, L., & Azouvi, P. J. (2007). Working memory after severe traumatic brain injury. *Journal of the International Neuropsychological Society, 13,* 770-780.

Verfaellie, M.

Williamson, D. J. G., Scott, J. G., & Adams, R. L. (1996). Traumatic brain injury. In R.L., Adams, & O. A., Parsons, & et al. (Eds.)*, Neuropsychology for clinical practice: Etiology, assessment, and treatment of common neurological disorders* (pp. 9–64). Washington, DC, US: American Psychological Association.

Wilson, B. A. (2002). Management and remediation of memory problems in brain-injured adults. In A. D. Baddeley, M. D. Kopelman, & B. A. Wilson (Eds.), *The handbook of memory disorders* (pp. 655–682). Chichester, UK: John Wiley & Sons.

Wilson, B., Cockburn, J., & Baddeley, A. (1985). The Rivermead Behavioral Memory Test. Reading England: Thames Valley Test Co.

Wright, M. J., Schmitter-Edgecombe, M., & Woo, E. (2010). Verbal memory impairment in severe closed head injury: The role of encoding and consolidation. *Journal of Clinical and Experimental Neuropsychology, 32,* 728-736.

Wright, M. J., Wong, A. L., Obermeit, L. C., Woo, E., Schmitter-Edgecombe, M., & Fuster, J. M. (2014). Memory for performed and observed activities following traumatic brain injury. *Journal of Clinical and Experimental Neuropsychology*, *36*(3), 268-277.

Zec, R. F., Zellers, D., Belman, J., Miller, J., Matthews, J., Ferneau-Belman, D., & Robbs, R. (2001). Long-term consequences of severe closed head injury on episodic memory. *Journal of Clinical and Experimental Neuropsychology, 23,* 671-691.